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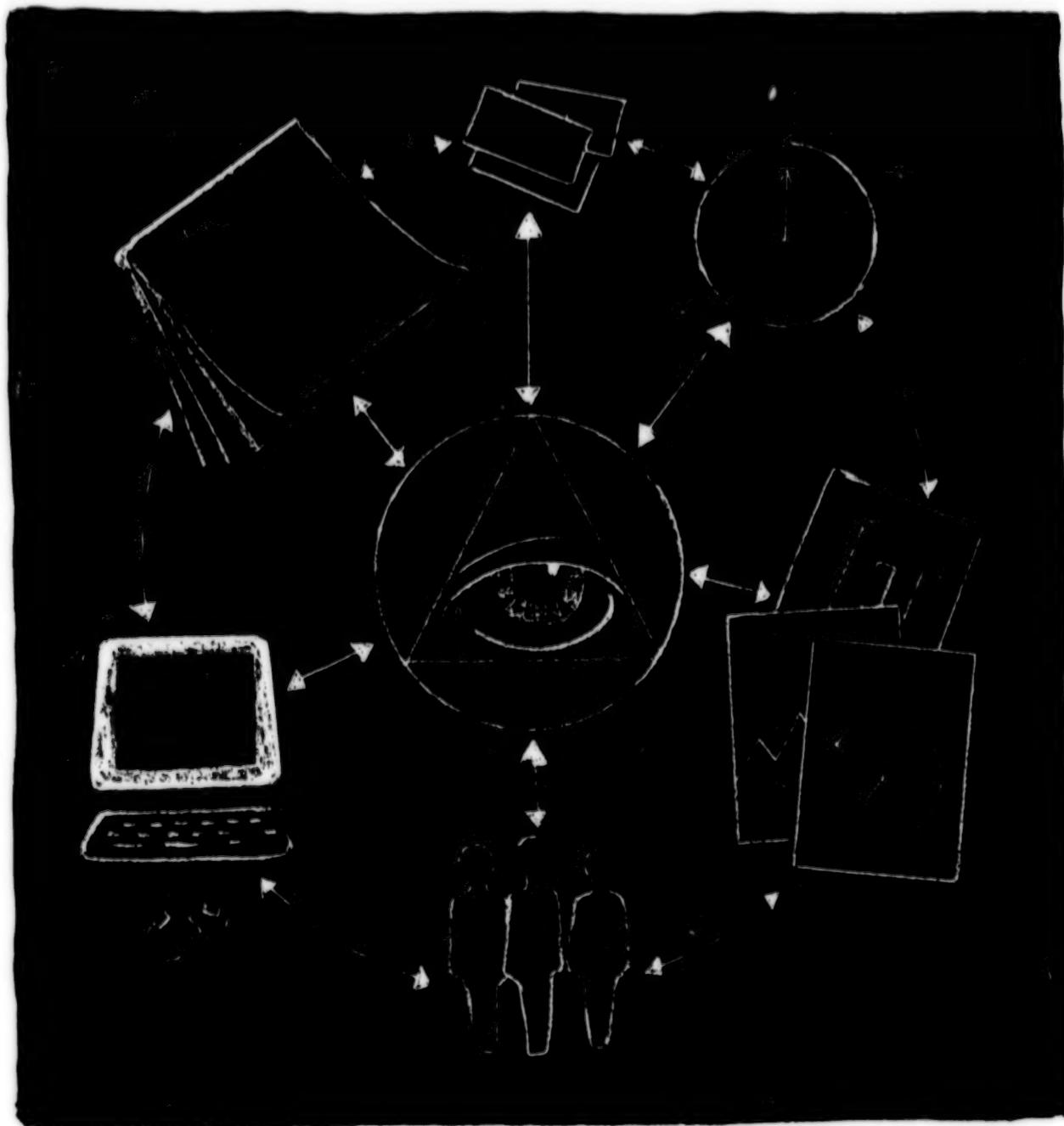
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READINGS IN PROGRAM CONTROL

Edited by Francis T. Hoban, William M. Lawbaugh and Edward J. Hoffman

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Scientific and Technical Information Office
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On our cover:

The center of any project is program control, keeping an eye on scheduling (the calendar), data management (the computer), resource management (people), reporting and reviewing (charts), time management (the clock) and, of course, budget management, signified by the dollars.

READINGS IN PROGRAM CONTROL

Introduction by Francis T. Hoban, William M. Lawbaugh and Edward J. Hoffman

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INTRODUCTION

by Francis T. Hoban, William M. Lawbaugh and Edward J. Hoffman

In a classic fable on individual perspective, several blind men are touching different parts of an elephant. Each individual is certain of something different as the object or animal is identified. All of them, of course, are wrong and in complete disagreement as to what they are handling. The moral of the story is the importance of always getting a variety of perspectives before coming to a decision, and realizing that none of them may be fully accurate or complete.

When it comes to the management of complex projects, it seems that such a lesson can never be forgotten. In particular, when it comes to the issue of program control, there are so many different possibilities, perspectives and opinions that it is easy to confuse the parts for the whole.

In the present environment of increasing scrutiny and budget reductions, it is critical that this area be integrated effectively in the management of any project. This collection of readings is aimed at shedding some light and offering a diversity of views in this area.

In contrast to the term 'systems engineering,' there has been general agreement in NASA as to what functions should be included under the term 'program control' and a lively debate about where program control functions should reside and who they should report to. Despite this ongoing debate, projects continue to be managed successfully; program control functions are being performed at NASA and status is being communicated to project management teams.

In NASA's earlier days, particularly during the Apollo era, the performance and schedule aspects of program control were developed to a fine art, with cost of far less importance.

Performance and schedule functions were absolutely vital to the success of the Apollo program. NASA led the world in its ability to manage a large, complex system using the relatively new and innovative techniques of program control.

Post-Apollo NASA has applied program control processes in a less rigorous manner, largely because the many smaller projects that followed could not afford the enormous costs associated with NASA's complex control systems. With the initiation of the Low Cost Systems effort in the mid-1970s, cost estimation and control became paramount. Cost has been a full partner to schedule and performance functions ever since.

Readings in Program Control, like its companion volume, *Readings in Systems Engineering* (SP-6102, 1993), is primarily for the next generation of project managers. As part of the corporate memory of the NASA Program and Project Management Initiative, this volume attempts to collect, preserve and transmit the lessons learned on program control for better management of the future. It is a well known fact of human nature that those who fail to learn from the successes and failures of the past are destined to repeat past mistakes.

We begin with the former Comptroller of NASA, Bill Lilly, who "wrote the book" on Program Control for the Agency. Kelley Cyr of the Johnson Space Center follows with the latest on cost estimating methods.

These overview pieces are followed by a group of articles on planning and scheduling. David Christensen, a professor of accounting at the Air Force Institute of Technology, examines cost overruns in the defense industry.

Dorothy Pennington and Walt Majerowicz look at program control in a current project. Pennington joined the Tropical Rainfall Mission as Deputy Project Manager, Resources; joint author Majerowicz of Computer Sciences Corporation is Schedule Manager.

Nancy Abell, Chief of Administration and Resource Management at Goddard Space Flight Center's Space Sciences Directorate, describes Goddard's Performance Measurement System. Gerry Longanecker, Senior Principal Staff Member in the Space Science and Applications Group of BDM International, Inc., explains scoping a program and scheduling. He is former Director of Flight Projects at GSFC.

A landmark piece by former NASA Deputy Administrator George M. Low closes out this book of readings. This piece is based upon a speech he gave in 1972 to a joint symposium in Washington of the Armed Forces Management Association and the National Security Industrial Association. As a consequence of these innovative ideas, Low set up NASA's short-lived, useful Low Cost Systems Office.

Two of the readings are excerpted from classic texts in the evolution of program control. The 1968 scheduling guide for program managers from the Defense Systems Management College contains excellent but hard to find charts and graphs for better program control. Marshall Space Flight Center's approach to program control development is one of the best available anywhere.

John D. Hodge, respected author, and veteran cost estimator Joe Hamaker of Marshall Space Flight Center, survey the history of estimating through various cultural changes. Humboldt Mandell, Jr., Head of the Exploration Programs Office at Johnson Space Cen-

ter, defines the major issues of program management related to cost estimation practices. Bill Keathley, former Associate Director of Programs at GSFC, offers nine advantages of cost plus award fee contracts. Ignacio Manzanera, CCE, with ARAMCO in Saudi Arabia, describes the planning and scheduling systems with easy-to-follow tables.

John R. Biggs and Walter J. Downhower show how program control techniques led to the notable success of a NASA development project, the 1973 Mariner Venus/Mercury Project. Downhower was the Systems Design and Integration Section Chief at the Jet Propulsion Laboratory. John Biggs had worked in procurement for the U.S. Air Force and later for NASA's Office of Space Science.

The editors gratefully acknowledge the authors for sharing their information with us and with you. We also wish to thank the Program/Project Management Initiative (PPMI) Librarian, Jeffrey Michaels, for his support. Thanks must also go out to the entire NASA family for their contributions to the art and science of program control. In this age of new program constraints and challenges, we agree with George Low, who thought that effective program control "is as great a technological challenge as everything else we have done in space."

Finally, the editors thank George Mason University, where two of us served as Senior Fellows in The Institute of Public Policy (TIPP) in 1993 and 1994 during much of the research and editing of this volume. Thank you, especially, to TIPP leaders Kingsley Haines and Roger Stough for the accommodations at the Center for Innovative Technology in Herndon, Virginia, a grand place to think and work. The views of the authors are their own.

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PROGRAM CONTROL IN NASA: NEEDS AND OPPORTUNITIES

by a Study Team of the National Academy of Public Administration

William E. Lilly, Project Director

The National Aeronautical and Space Administration (NASA) has successfully managed some of this country's most complex technology and development programs. These successes have included the application of sound program control processes. The impetus for this study arose from the NASA Management Study Group findings that over time, some program control tools and disciplined procedures and processes had weakened. The Study Group recommended that steps be taken to establish a comprehensive training approach in program management, and specifically, in program control functions. This study looks at program control processes within NASA currently in use, defines a "model" of program control functions, and provides recommendations on program control training needs and opportunities.

In 1988, NASA Headquarters tasked the National Academy of Public Administration (NAPA) to examine the processes and systems used by NASA to manage and control program and project activities. Essential elements of a program control system include program development planning and documenting program requirements; integrated scheduling; resources management; configuration management; documentation and data management; establishment of essential baselines; and the conduct of performance reviews. Specifically the NAPA study was designed to include:

- Determination and definition of program control functions as currently practiced in NASA.
- Definition of a model of program control functions for NASA.
- Observations on training of personnel.

- Generation of recommendations for training in program control objectives and processes at the basic, intermediate and advanced levels of project management.

The impetus for a program control aspect of program and project management training and developmental efforts can be traced to a series of findings and recommendations on strengthening program management and control functions which were derived from the Rogers Commission and the NASA Management Study Group (the Phillips Committee) reports. In reviewing the total function of NASA program management, the Phillips Committee found the weakest area to be that of program planning and control. Committee members commented that over time NASA's use of program control tools and disciplined procedures and processes had weakened. They recommended the reinstitution of a Program Approval Document system and a revitalized hierarchy of program/project status reviews against approved baselines. In addition, the Study Group recommended that steps be taken to develop a comprehensive training approach in program management, specifically in program control functions, that would be based on real experience.

The significance of the program control functions within NASA cannot be overstated. The success of large and complex research and development projects depends on commitment, diligent and disciplined attention to numerous planning, resource and scheduling variables, and the integration and balancing of complex, interrelated activities. Along with the systems engineering function, the program control function is one of the most important activities in successful program/project management. Systematic and disciplined attention to the implications

of variances between planned baselines and actual performance on development projects is critical to taking early remedial action, reducing costly delays and achieving success.

The purpose of this study is to indicate the areas of need as well as provide guidance to the development of training opportunities concerned with program control in support of effective program/project management in NASA. The study could not have been completed without the assistance of NASA employees at field Centers and Headquarters. Their contributions helped the staff to understand the application of project control functions at different Centers. Special thanks are owed to Frank Hoban, Program Manager, NASA Program and Project Management Initiative, who provided the Academy with the environment to pursue the study.

The Program Control Function

In NASA, a project ". . . is a defined, time-limited activity with clearly established objectives and boundary conditions executed to gain knowledge, create a capability, or provide a service." Major space research and development projects in NASA typically include design, development, fabrication, test, and flight operations. A program/project manager is designated responsible for ensuring the performance of all functions necessary for management of the project. The three basic elements of the manager's job are technical performance, cost and schedule. The program/project manager needs to know where the project is at any point in time and to identify and scope problems early. Program/project control, which aids the project manager in this regard, is the total management process of establishing and maintaining program baselines and effectively supporting the project manager in meeting the overall objectives of the project.

The combination of functions of program control is an essential element of the program management process. The establishment of

comprehensive performance requirements by systems engineering provides the details and parameters necessary for program control to maintain a comprehensive, adequately explicit and integrated program plan. This plan documents and defines program requirements and establishes the official baselines of program content, scope, configuration, schedule and cost. A comprehensive program control process includes procedures for reporting and reviewing performance against baselines; analyzing and synthesizing program performance; evaluating alternatives; developing disciplined processes for considering, approving, and implementing changes to official baselines; and assuring positive feedback on all directions and decisions. It also provides a uniform system of program documentation and assures clear and consistent communications throughout the program community on program progress, status, and issues. The integrated operation of these functions furnishes the means to determine the harmony of actual and planned cost, schedule, and performance goals during development and fabrication by verifying whether everything is occurring in accord with baseline plans. The larger point is clear: a program control system requires sustained attention to the system as a totality, rather than as a group of parts.

Ultimate responsibility for the effectiveness of program management control rests with top management. Top management decides upon Agency strategy, policy, and organizational and accountability structure. The control system is a set of major tools and procedures for implementing those decisions and for forming coherent and defensible strategies to cope with changed and changing circumstances. For the most effective program management and control to exist, an *environment* of accountability of organizations and individuals needs to exist at the top of the Agency. It should be clear to the entire Agency how NASA intends to operate and what is expected of all elements. Delegations

of authority, definitions of roles and assignments of responsibilities should carry with them the terms of accountability. Disciplined processes for obtaining required feedback on delegations and for measuring and systematically reviewing performance on programs and projects should exist. The pattern of program reviews against approved program baselines should also be established at the top. This can consist of separate reviews or be a part of the general management review process, but a disciplined approach of reviewing status against approved baselines by the Administrator and/or the Deputy is needed. The strength of such an approach is that it allows Agency leaders to directly, programmatically and effectively keep tabs on the performance and potential pitfalls of programs. This in turn enables top managers to identify and consider the implications of both "inside" factors and "outside" factors, forces and trends which are likely to have an effect on NASA and its missions.

A number of characteristics distinguish NASA research and development projects, including:

- *Uncertainty.* Many of the processes and products to be developed will be undertaken for the first time and all components require the performance of advanced technologies.
- *Long lead times in development and fabrication.* This necessitates concurrent development of elements and subsystems and the fitting of end products together. It requires a high order of advance planning and detailed monitoring and tracking and increases the need for testing (component testing, subsystem testing and system testing).
- *Size and complexity of projects and the large number and dispersion of participants.*

- *Persistent scrutiny of projects by the public, the Congress and the scientific community.* Not only must the work be done well, the project manager must be prepared to interpret, explain and defend what is being done and why. Practices and standards for public projects far exceed typical industry standards.

Against this background, it is important to keep in mind that good program management is a matter of balancing different internal and external factors so that performance is maximized over the longer term. Program control interventions, if used correctly, help to maintain this balance.

Major Functions of Program/Project Control

The basic control functions for development projects are planning, configuration management, scheduling, resource management and data management. In some cases procurement activities and other business management activities may become part of the control function, as well as logistics and separate activities for program analysis, management information and program reviews. The combination of activities included depends upon the size and complexity of the program or project, the existing support structure and the preferences of the Centers and the individual managers. Regardless of the individual functions, more than anything else in program control, it is important for the personnel to see and comprehend the totality of the job to be done and to thoroughly understand the interrelationships and interfaces of the subsystems and systems, as well as the organizations and participants in the project. Another important element in structuring and carrying out program control functions is uncertainty and the inability to completely eliminate it. Uncertainty should be specifically considered in program planning, scheduling and resource planning.

Program Plans and Requirements

The development plan is the basic plan for execution of the program or project. It is the top-level requirements document and the top-level implementation plan. It is the single authoritative summary document that sets forth the manner in which the objectives shall be accomplished. It defines the program organization, responsibilities, requirements, resources and time phasing of the major actions required.

Program planning sets forth the development requirements needed to establish and maintain an integrated planning baseline of what is to be done, how it is to be done and when it is to be done. It is not a one-time process, since the development of detailed performance requirements are not established at one point in time. In addition to the technical requirements, detailed management and mission requirements should be established. It is a continuing process of laying out and ensuring a unified effort in implementing the program, adjusting to changing conditions, maintaining the program or project development plan, and integrating ongoing technical requirements. Although planning steps are laid out in a linear sequential manner, the process is iterative.

The technical requirements establish the work packages. The development of the project work breakdown structure (WBS), consistent with the Agency coding structure, may also occur in conjunction with the planning function or it may be part of one of the other functions. On NASA development projects the WBS will normally be end-item oriented rather than discipline oriented.

Resources Management

Resources management includes the establishment, monitoring, and maintenance of obligation and cost as well as the manpower baselines. Manpower constitutes the vast majority of development costs, and knowledge of status and trends are extremely im-

portant. The reporting structure for cost should be established and maintained with an emphasis on cost phasing and cost to completion. Reporting systems and selection of report items should be designed to raise questions, not to answer them; the implications are important, not the absolute value recorded. The absolute value is useful only for historical and legal purposes.

The planning of reportable items is usually achieved through use of the Work Breakdown Structure accounts. The structure and analysis of report implications should be correlated closely with schedule and technical performance. The recording and reporting of cost alone has little or no value as related to performance implications in the future; one of the main purposes of resource and schedule analysis is to recognize implications and to reduce management surprises. This allows for identification and evaluation of "what ifs" and alternatives. The initial and subsequent cost estimates must recognize and quantify risks and uncertainties and provide reserves and allowances for program changes. The requirement for uncertainties and risk is as vital to project success as any other cost element. Having contingency funds available and using them judiciously are integral parts of successful research and development efforts.

If the contractor reporting structure attempts to closely parallel schedule and cost reporting milestones, extreme care should be taken that it is not based on the assumption of equal value milestone performance. This type of system can easily lead to some misleading assessments. If such a system is used, program changes can completely disrupt performance reporting and require installation of a new structure of report accounts and a long hiatus in reporting. To base a system on an assumption of continued program equilibrium would be a mistake—uncertainty is much more likely to be the norm.

Configuration Management

The purpose of configuration management is to provide a disciplined systems approach for the control of the requirements and configuration (normally established by systems engineering) of hardware and software to be developed and the process for change consideration. The function basically consists of four distinct practices:

- **Configuration Identification**—The definition and establishment of the total technical requirements (performance and functional) and the detailed configuration definition and documentation. Configuration identification is usually established incrementally as design and development proceed.
- **Configuration Control**—The formal process used to establish and control changes to the configuration baseline. This control is effected through a hierarchy of formal configuration control boards established at the different levels of hardware and software.
- **Configuration Accounting**—Performance of this function "defines" the exact baseline on a continuing basis and provides a clear audit trail from the authorization of changes into the affected documentation. It should provide the single authoritative source for baseline definition.
- **Configuration Verification**—Ensures that the baseline configuration requirements have been incorporated into contracts and are fabricated and tested accordingly.

Documentation Management

Documentation management establishes data policies and responsibilities and procedures for identifying, planning, selecting and scheduling a large volume of data. The data management system ensures continual management review of NASA-generated and contractually required documents, eliminates

any non-essential requirements, and assures only the minimum amount of documentation necessary for effective program management. The principal intention of the system should be to define the information required, justify its need, and control the information after it is generated.

Schedule Management

This function provides for the development and maintenance of the master schedule and the detailed, interrelated schedules covering the total program or project to completion. It involves the requirement to define the schedule format, content and symbols used. A critical component of the function is selecting the key progress indices for measuring performance and indicating potential problems. A system of reports, reviews, and action feedback needs to be provided. Working closely with resources management, the analysts must evaluate performance, synthesize various inputs and implications, and generate and evaluate alternatives. Plans and schedules should provide for uncertainty and the unknown.

The integrity, reliability and discipline of the reporting system are essential. NASA should continually assure the end-to-end integrity of program control data from its source in subcontractors to prime contractors and subsequent levels of NASA. The importance of early problem recognition cannot be overemphasized: the ideal control system detects potential deviations before they become actual ones. The costliest aspect of a development program is time. Slippages in a program schedule are extremely expensive. A permanent record of all changes and slippages should be kept to allow trend analyses.

The primary steps of management accountability—establishing objectives and baselines, measuring performance against baselines, analyzing and evaluating performance and alternatives, assigning action or direction, and ensuring action feedback—are applica-

ble to the management of almost any activity. Some aspects of control functions such as planning, scheduling activities, and managing resources are also applicable in some degree on all NASA work, including applied research and technology, science tasks, and institutional management. However, the collection and staffing of the full array of project control functions are not necessarily appropriate for all activities within NASA. The style of management and types of controls require tailoring to the particular objectives and problems of the individual activities.

How program control functions are grouped organizationally is a consequence of a number of factors. Nevertheless, it is clear that all of the functions and their outputs need to be integrated. On a small project, a project manager could possibly perform the functions and integrate the data output. On relatively large or complex development projects or programs it is the opinion of the Academy team that management control and synthesis of program element progress and performance are enhanced by grouping the functions. A model that lays out program control functions suitable for most large and complex development projects is shown in Figure 1. This model assumes that program analysis is an inherent part of the functions shown. As a matter of preference, however, program analysis can be handled as a self-contained function.

Current Status of Program Control in NASA

As a part of this study, the Academy made an effort to ascertain the current status and health of program/project control functions and processes within NASA. Interviews and discussions were held in both Headquarters and Centers with Center Directors, directors of flight projects, program managers and personnel who play roles in program control functions. Discussions were also held with previous NASA program directors, some aerospace industry officials and support con-

tractors supplying management services to NASA.

In Headquarters, the reinstitution of the Program Approval Document (PAD) System has not moved swiftly. Dale Myers, Deputy Administrator in 1987, sent a letter with instructions for preparation of PADs in June 1987. On March 14, 1989, a management instruction (NMI 71211) was issued, which required the specific development of 23 separate PADs with provisions for adding or deleting projects in the future. Approximately eight have been prepared and approved. The Deputy Administrator is holding meetings with program offices in an attempt to tailor the format, content and level of detail of the document, and to define the management processes to fit the desired methods of operation in an orderly and efficient fashion.

Since early in its history, NASA documented its management policy and principles of project management as well as instructions on planning and approving major research and development projects. These instructions were canceled in the mid-1980s when the PAD system was eliminated. Efforts have apparently been made to reinitiate or replace some of the canceled documents, but at this point, it has not been accomplished. An understanding of how the Agency intends to operate and what is expected in terms of project management approaches and techniques does not currently exist within the Agency. A common concern among senior managers at the Centers was the apparent lack of appreciation of the usefulness of such policy statements on the Agency's operation.

General management status reviews continue to be held at Headquarters. The current review system provides for three separate meetings—one for Space Transportation and Space Station, another for all other programs and projects, and a third for institutional activities. According to some attendees, these reviews could not be characterized as disci-

lined reviews of progress against established baseline milestones and goals. However, program offices participating in these reviews do characterize the status and problems of projects.

The organization and performance of program/project control functions within the program offices and the development Centers have not materially changed or improved since the Management Study Group findings in 1986 and 1988. There have been some changes in personnel and in the methods of performing the functions. One trend appears to be an increasing use of support contractors to provide some project control functions including scheduling, configuration management, data management, and elements of financial operations. The degree of contractor

use varies among the Centers but the trend [in 1989] appeared to be growing throughout NASA in all functions and activities in addition to program control. The impetus for contracting out functions was generally attributed to the need for supplementing the limited availability of civil servants. Discussion with one NASA support contractor, however, confirmed that contractors also had the same difficulties in finding skilled personnel in program control disciplines and were faced with a problem of how to train their people and how to sharpen their skills.

In reviewing the list of program control functions with NASA Center personnel, the reviewers found no disagreement that all of the program control functions were required and should be performed on development

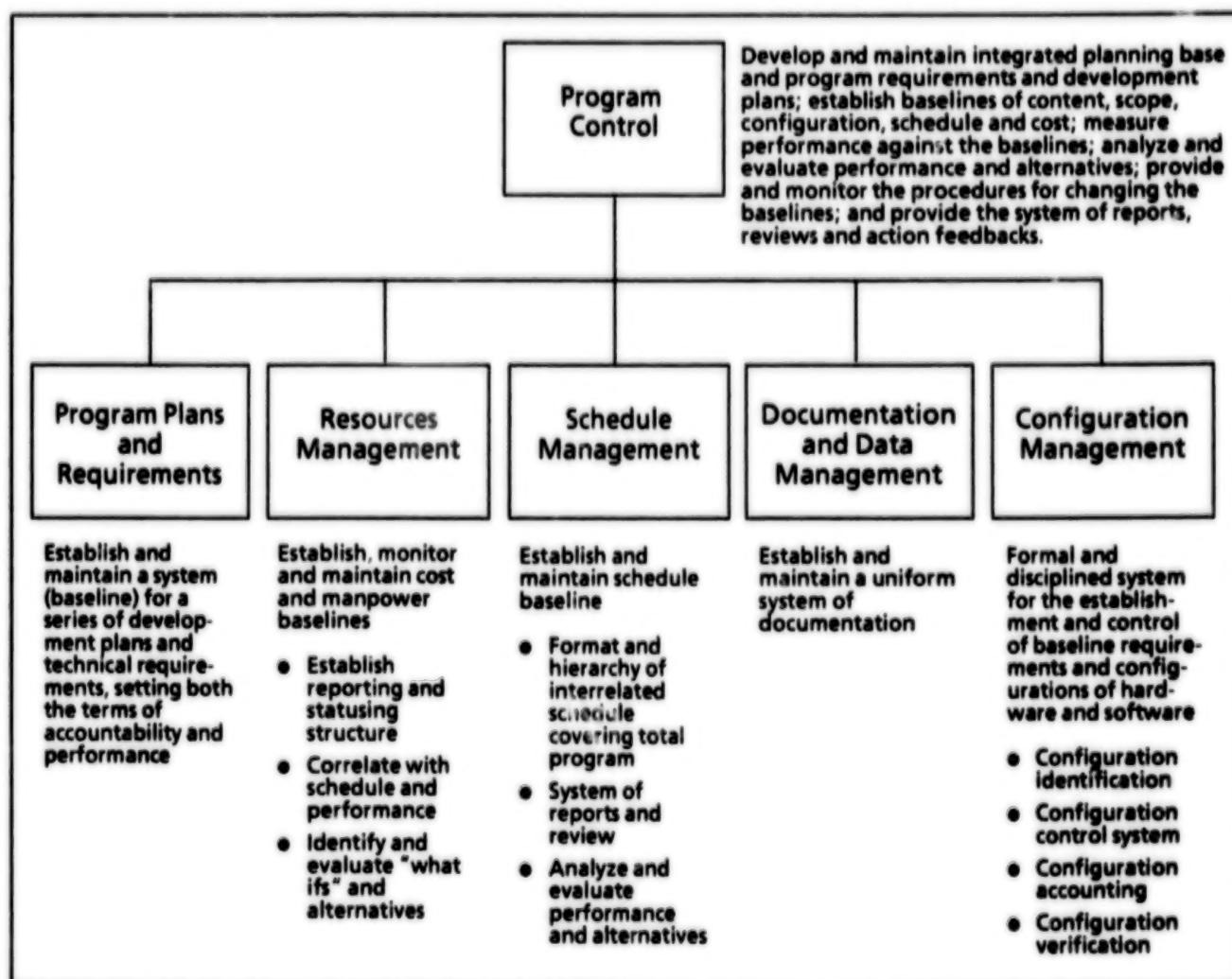


Figure 1. Program Control Functions

projects. Only two organizations had essentially all of the program control functions operating together in one group. At Goddard Space Flight Center the functions were all within the Project Director's office reporting to the Deputy Director for resources. Scheduling, configuration management and data management functions were performed by a support contractor and were under civil service monitors responsible for the functions. A discrete function for project planning was not within the project offices. The Space Station office at Johnson Space Center (JSC) is the other organization having a fairly complete grouping of functions under the program control division. In the other program offices at JSC, program control functions are not integrated in one group but are being performed in one way or another in various organizations.

At the Lewis Research Center, steps have been taken in the Space Station project to integrate resource management, scheduling, and configuration management in a program control organization. At the Marshall Space Flight Center, there is a fairly consistent pattern of combining scheduling and resources management in a single organization in the project offices. Except for the cases noted above, the remainder of the NASA Centers and the Headquarters program offices do not have organizationally integrated program control functions. The functions are either not performed, are scattered in various subgroups, or are done informally.

An Agency cost estimate is always prepared on new development projects prior to evaluation and selection of contractors. However, there does not appear to be a uniform procedure for recycling and validating new estimates after selecting the development contractor. Rather, the contractor's negotiated bid generally becomes the baseline against which any changes are incrementally made. This is true even though the contractor's estimate is usually considerably lower than the

government's estimate. The rationale for the government's higher estimate in most cases is quickly forgotten. Credibility begins to be attached to the contractor's estimate, which is neither justified nor borne out by history. Since it takes some time for deficiencies to become apparent they generally come as surprises and result in more costly schedule slippages. In too many cases a large proportion of the time available to the staff of project resource and schedule management groups is spent on finding near-term funding solutions to these "surprises."

As a general observation, too little effort is spent by both resource and schedule groups in analyzing potential problems or risks and in selecting critical reportable milestones that could give some advance notice on the probabilities of problems. Close correlation of reportable schedule and cost performance data is desirable, but the critical indices of performance are not always precisely aligned with a hardware-driven work breakdown structure.

There is an apparent lack of emphasis on laying out logic diagrams or networks on projects, particularly prior to selecting schedule and resource reporting items. The researchers know of no better way to comprehend interrelationships and interfaces of efforts on components, subsystems and systems. When these networks are laid out in time sequence, critical schedule and resource reporting indices become much more apparent and risks are easier to assess. The special virtue of logic diagrams is that they allow planners to incorporate time, resources, and technology into strategies, thus linking temporal horizons with contextual changes.

As a generalization, reviews at the Centers appear to be more structured toward the assessment of project performance than they are in Headquarters. Many of the reviews at the contractor plants, however, seem to be primarily scheduled visits with fixed agen-

das, and with large groups spending great amounts of time looking at viewgraphs. It was not apparent how often site visits by project control personnel were made for the purpose of assessing performance and verifying the integrity of reported data at its source. Regardless of how scientific the approach or how sophisticated the management system and tools are, there is no substitute for a simple visual assessment. Coordination of those supplying performance data is essential.

Training

Traditionally within NASA, program control personnel have gained skills and knowledge through first-hand experience and from their experienced supervisors. Immersing themselves in program/project research and development activities is still the most common way of gaining project management knowledge. Forming mentor relationships—working with a person who can provide counseling, guidance and advice—is also used to gain the skills and credentials of program control. However, experienced program control personnel are becoming fewer within NASA. According to interviewees at the Goddard Space Flight Center, in the past, many program control staff first studied operations research or industrial engineering, then acquired on-the-job skills and subsequently passed on lessons learned by various means. Rarely did program control staff receive formal training related to specific functions such as the establishment and maintenance of a configuration control or scheduling system.

NASA and contractors currently face difficult problems in recruiting experienced program control staff due to a number of reasons, from limited career paths to elimination of industrial engineering disciplines at many major universities. As mentioned earlier, in response to recommendations from the Phillips Committee, NASA decided to formalize efforts to help in the development and training of managers, including program

control personnel. Formal training will be provided in such areas as resources management, schedule management, and configuration management. Analytical skills and the philosophical and logical foundations of program control, however, cannot be learned just by attending classes. They require application and the achievement of an end result as well. Self organization, program interest, ability to coordinate individuals and data, a questioning attitude, resiliency, sensitivity, imagination, and practicability are other nonempirical qualities that are valuable in program control work, but are beyond the realm of classrooms. In sum, formal courses can only complement, not replace, hands-on experience and the inherent qualities of key personnel. This is because analytical skills are, to a large extent, embodied in people and institutions, not just in physical objects like computers.

It is anticipated that formal development training will be provided by both civil servants and contractors. There will be a core curriculum which will be designed to serve business, technical and program and project management staff as well as a series of detailed courses designed for people who will be performing functions in specific areas. It is expected that the importance of integration of the program control functions and synthesis of data, personal responsibility and accountability, and disciplined procedures will be stressed. How the courses are structured and how consistent they are with the past experiences and needs of trainees will have a strong bearing on the prospects for success of the training efforts. Equally important, however, will be the support of top management at the Centers and Headquarters. Their interest will have a serious impact on the outcome of the project. If top management is sensitive to and supportive of the need for training and displays a strong commitment to the training program, the probability of success increases tremendously. Perhaps more significant is that if top management is

involved and accurately communicates its involvement, the entire effort will be perceived as credible and worthwhile.

Recommendations and Observations

NASA has successfully managed some of this country's most complex technology and development programs. These successes have included the application of sound program control processes. The basic concepts of program management and program control have not changed, although computerized systems have the capability to enhance the quality and effectiveness of documentation, communications, evaluation tools and support systems. Much of the new capability of tools and support systems have been incorporated in NASA, but over time NASA's use of the basic management control disciplines has weakened. Strengthening program control involves the improvement and utilization of certain disciplines, the existence of a conducive Agency environment and an understanding throughout the Agency of the leadership's policy and objectives. The following recommendations are oriented toward improvements in program control processes and practices.

Enhancement of Agency Environment for Effective Program Control

This study concludes that it would be extremely helpful for NASA personnel to be aware of the importance attached to program control functions by the Office of the Administrator. This awareness can result in the reinvigoration of program management disciplines throughout the Agency. An effective method of informing Agency personnel and contractors would be through appropriate issuances setting forth Agency intentions for conducting its business, expectations of all elements and policies and procedures for program/project approvals, assignment of responsibilities and the explicit accountabilities of organizations and individuals.

The following actions would be helpful:

- Issuance of Agency policies and processes for the approval and conduct of projects, the assignment of responsibilities and the terms of accountability of organizations and personnel.
- Establishment of regular performance reviews against approved baselines of development plans, schedules and cost appropriate for this level of management.
- Facilitation of rapid communications to and from all NASA elements regarding program control functions, tasks and feedback on action assignments.

Development of Training Activities for Program Control

The primary emphasis should be on understanding the role of program control functions in relation to and in context with the program/project manager and other groups and functions of the program office, particularly systems engineering. Systems engineering includes those activities required to transform mission needs into a comprehensive and definitive set of systems performance requirements. It also includes the activities needed to define a preferred systems configuration and its detailed performance requirements. The results of these activities set much of the baseline detail for program control functions including program plans and configuration management and parameters for schedule and cost management.

Program control is the total management process of establishing and maintaining the official development plans and program baselines in a manner which maximizes success in meeting a program's overall objectives. Although the following topics are not all-inclusive, some suggested program control training activities are (more detail shown in Appendix A):

1. Philosophy, content and context of effective program/project control.

2. Planning and documentation of requirements.
3. Content and processes of configuration management.
4. Logic diagrams or networks.
5. The scheduling function and process.
6. Basics of primary methods of cost estimating.
7. Resource management and control.
8. Presentation of data.

The most important element in evaluating and assessing the status of a project and providing program control is the understanding of the objectives, technical content, development approach, and the interrelationships and interfaces involved in its development. Throughout this report, the Academy researchers have taken the position that program control is not a collection of the separate functions that comprise it, but that it is an understanding of the plans and approach and the interrelationships of the functions and performance of configuration, schedule and resource management.

The most meaningful implications from performance data cannot be drawn from the independent functions, but rather, only when the data are integrated. For this reason we have emphasized the integrated understanding of the roles rather than skills and tools. Tools and skills can be very important but only when one understands their limitations as well as advantages and knows when they can be usefully applied. In this context, emphasis on skill training is important with regard to particular tasks such as logic networks, a means of focusing data for the maximum information output and the presentation of interrelated performance data.

Observations

Until conducting this study it had not been apparent to the researchers the degree to which NASA has become staffed with support contractors as opposed to career civil servants. On-site contractors appear to now exceed civil servants. The impact of this condition potentially can have serious consequences on NASA's program management and control capabilities.

As stated earlier in this report, NASA projects push technology beyond the current state of the art. Traditionally NASA has had the civil service and fabrication capability in its centers to conduct the appropriate depth of studies, examine objectives and missions, develop the technical concepts for accomplishing missions, determine feasibility, and provide the conceptual design. If it was decided to budget and contract for the design and development of a project, the inhouse capability existed to manage, technically monitor, evaluate, and direct such contracted work. If technical problems arose at the contractors' plants, the capability existed to help provide solutions and correct the problems. Some of the major objectives of program/project control are the early identification of potential problems, avoidance of surprises, provision of workarounds, and the ability to obtain help in providing solutions. This precept of the importance of early problem identification assumes the availability of the technical capability to participate in solutions to such problems.

Funding pressures on projects have continued since the early 1970s and less funding allowance for the contingencies of the "unknown" has been the result. As surprises occur and additional funds are not available, schedules usually become the variable on which short-term solutions to fiscal year funding problems are based. The obvious result is an increased run-out on total cost and shrinking credibility.

With the increasing contractor staffing, NASA engineers have less and less "hands-on" experience. Service contractors are increasingly being used at Centers to perform project control functions such as scheduling, configuration management and elements of financial management. In effect, this is using contractors to monitor the performance of prime development contractors. This situation is leading some NASA managers to

question the Agency's continuing ability to manage contracted projects and control costs.

NASA remains responsible for the performance of the work, but with a reduction in capability to influence and correct performance. How well the Agency meets demands relating to program performance has a major effect on its ability to effectively run programs.

Appendix

Suggested Training Activities

The following topics are not inclusive in the sense that they cover all items.

1. **Philosophy, content and context of effective program/project control.**
 - What is meant by "control"?
 - An explanation of how the main functions relate to each other.
 - Importance of understanding the totality of the project.
 - Importance of understanding interrelationship of elements and interfaces.
 - Importance of ensuring integrity of reported data to source level.
 - Importance of concentrating on the implications of reported data rather than on the factual data.
 - Anticipation of development difficulties and changes in external environment.
 - Continual assessment of "what ifs."
 - Importance of a questioning approach.
 - Requirement for disciplined processes and positive monitoring.
 - Barriers to effective program control.

2. **Planning and documentation of requirements.**
 - Importance of maintaining development plan baseline.
 - The necessity of a series of subsidiary plans, actions, and schedules.
 - Documentation of requirements.
 - Technical and program reviews and results.

3. **Content and processes of configuration management.**
 - Importance of early development and documentation of configuration requirements and preparation of a configuration maintenance plan.
 - The systematic approach of defining and documenting the detailed configuration. Understanding of the need for incremental identification as design and development proceed.

4. **Logic diagrams or networks.**
 - Understanding how to develop networks.
 - Importance for understanding the total job and the interrelationship of the components of the job.
 - Relevance of networks to effective analysis and synthesis of performance data.

5. **The scheduling function and process.**
 - Critical importance of identifying known and potential development risks.
 - Planning for the unknown.
 - Understanding interrelationships and interfaces of development processes and organizations.
 - Importance of selecting the critical indicators of progress or problems – the most important scheduling function.
 - Identification of indicators as far "up-stream" as possible from critical progress points.
 - The danger of becoming mesmerized with systems. The need to understand weaknesses better than positive elements and to keep systems as simple as possible.
 - The amount of time required for administrative and decision processes. This time requirement cannot be overlooked.
 - The costliest aspect of a R&D project is time. Slippages are extremely expensive.
 - Emphasis on early problem recognition.
 - Importance of having only authenticated and dated schedules.
 - Maintenance of permanent record of all changes and documentation of slippages.

6. Basics of primary methods of cost estimating.

- Understanding of concepts, processes, when each is most useful, advantages and disadvantages:
 - Parametric cost estimating;
 - Analogy estimates;
 - Engineering estimates ("grassroots", "bottom up"); and
 - Expert opinion or Delphi techniques.
- Dangers of accepting contractor's negotiated cost estimate without complete re-verification.
- Importance of quantifying risks.
- Importance of provision for and use of reserves.
- Risks involved in using cost goals as incentives in cost estimating and the use of "design to cost" concepts on R&D operational systems.

7. Resource management and control.

- Establishment of a cost reporting system.
- Importance of correlating manpower reports on R&D projects.
- Importance of integrating cost data with schedule performance.
- Verification of end-to-end integrity of data reported.
- Understanding the contract structure, and nuances of differences in definitions

and accumulation processes of prime and subcontractors.

- Importance of on-site verification of data and calibration of personnel supplying data.
- Reporting of data should raise questions, not answer them.
- Trend analyses.
- Emphasis on run-out and cost to completion.
- Importance of continual work on "what ifs."

8. Presentation of data.

- Determination of objective or purposes of presentation: What is the message or information to impart?
- Determination of desired outcomes.
- Avoidance of reams of cost, schedule or engineering data. The need to focus presentations and use only data which contribute to understanding context, significance and implications of information. Detail can overwhelm strategic choices.
- Factual data may or may not be significant to future actions or decisions even though they may be important for legal or audit purposes.
- The need to sequence messages in a priority, logical or temporal order. The use of unambiguous language.

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COST ESTIMATING METHODS FOR ADVANCED SPACE SYSTEMS

by Kelley Cyr

NASA is responsible for developing much of the nation's future space technology. Cost estimates for new programs are required early in the planning process so that decisions can be made accurately. Because of the long lead times required to develop space hardware, the cost estimates are frequently required 10 to 15 years before the program delivers hardware. The system design in conceptual phases of a program is usually only vaguely defined and the technology used is so often state-of-the-art or beyond. These factors combine to make cost estimating for conceptual programs very challenging.

This paper describes an effort to develop parametric cost estimating methods for space systems in the conceptual design phase. The approach is to identify variables that drive cost such as weight, quantity, development culture, design inheritance and time. The nature of the relationships between the driver variables and cost will be discussed. In particular, the relationship between weight and cost will be examined in detail. A theoretical model of cost will be developed and tested statistically against a historical database of major research and development projects.

Cost Theory

In order to meet the needs of NASA for a long-range forecasting tool, the following requirements were laid down:

- Must have the ability to predict cost over long time horizons (25 to 50 years).
- Must be valid for substantially different types of systems.
- Must be able to predict cost reliability despite significant technological advances.
- Require few inputs and be simple to use.

In order to determine the feasibility of a model that would meet the specified requirements, a proof of concept test was devised. A theoretical model was developed for predicting the total acquisition cost of a major hardware development program. The variables used in the model are described below.

Quantity Variable. The relationship between the quantity or number of units produced can take many forms. In Figure 1, four of the most common forms are illustrated. Figure 1a illustrates the unit or average cost method in which the average cost per unit is used. In this case, the average cost is the same regardless of the quantity produced. This method is most useful for small quantity buys of commercial products where the quantity purchased does not materially affect the cost of production.

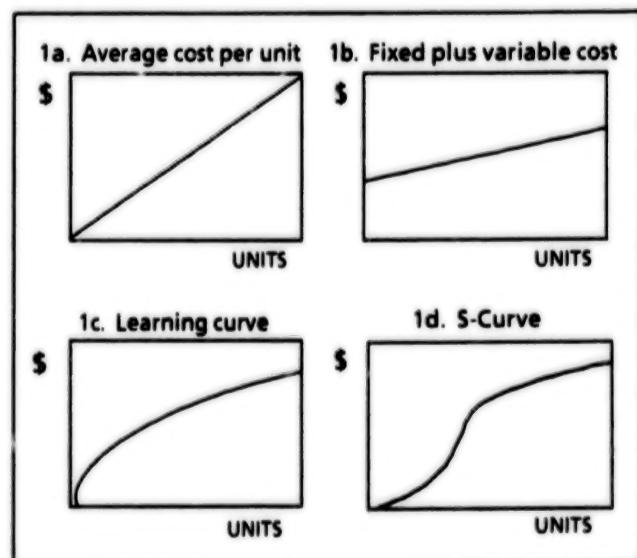


Figure 1. Total Cost Versus Quantity

A second method of estimating cost, illustrated on Figure 1b, is the fixed plus variable cost method. The marginal cost, in this case, is constant. The average cost is higher than the marginal cost, decreases as the quantity

increases and approaches, but never reaches, the marginal cost. In this case, the fixed cost is relatively large and changing the quantity produced can substantially affect the average cost. This model represents increasing economies of scale.

The third method, illustrated in Figure 1c, incorporates the principle of decreasing marginal cost. In other words, the additional cost of each unit is slightly less than the previous unit. This principle is also known as the learning curve or experience curve. The learning curve also has decreasing average unit cost as the quantity is increased.

A fourth type of quantity relationship is shown in Figure 1d. In this case, the marginal cost increases for the first several units, then begins to decrease along the lines of a learning curve as quantity increases further. This example would represent a situation where the first few units were partially operational or low cost prototypes were gradually building up to full scale production articles. Once a reproducible configuration is reached, the marginal cost decreases according to learning curve principles.

Weight Variable. Weight has been used for many years in estimating the cost of aerospace systems. It is a most convenient variable since it generally characterizes the size and often, the performance of a piece of hardware. Weight is also a key engineering parameter; therefore, an estimate of it is usually available, even at the early stages of a program. Although the emphasis here is on weight, the discussion could also be applied to other descriptive parameters such as size, speed, power, etc.

The following discussion refers to weight as the dry mass of a single unit. Like quantity, weight can be related to cost in several ways. The most common relationships are depicted in Figure 2.

The simple cost-per-unit weight relationship is illustrated in Figure 2a. By definition, the cost-per-unit weight model has constant average cost-per-unit weight.

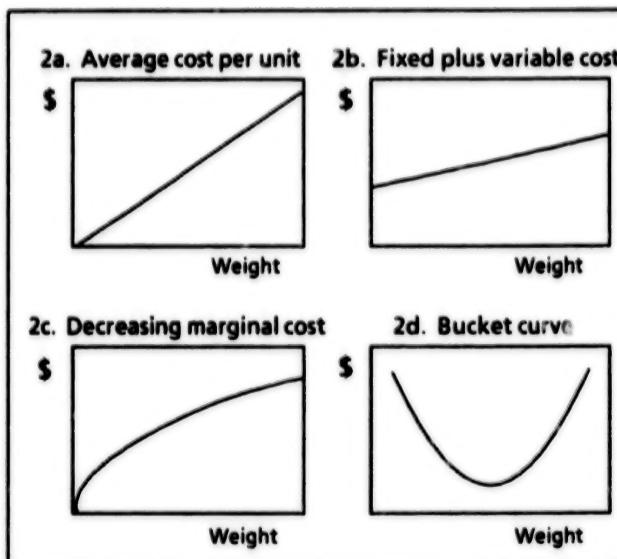


Figure 2. Total Cost Versus Unit Weight

The model in Figure 2b has the characteristic fixed plus variable cost. In this case, the average cost per unit weight decreases as the weight increases. The marginal cost is constant and average cost is asymptotic to marginal cost. This is a case of economies of scale with respect to unit weight.

Figure 2c illustrates a model in which the marginal cost is decreasing; hence, the average cost is decreasing. In this case, the rate of change in the marginal cost is also decreasing.

The total cost relationship shown in Figure 2c is an exponential growth function. The exponent happens to have a special meaning in economics: it is the elasticity of cost with respect to weight. If the elasticity is greater than 1, then the relationship is said to have decreasing economies of scale. If the elasticity is greater than 0 but less than 1, then there are increasing economies of scale. If the elasticity is exactly 1, then there are constant economies of scale.

Clearly, if there are strong economies of scale, it would be better to build larger (heavier) things. It should be noted, however, that weight and quantity may also be related. The larger something is, the less likely it is to be built in large quantities. The relationship between cost and quantity may also have economies of scale; therefore, the effect of different weights on both cost and quantity should be considered when estimating total program cost.

In the last case, Figure 2d, the marginal cost weight is negative up to a certain weight, then becomes positive. The total cost curve becomes U-shaped (also known as a bucket curve). This curve represents a situation where there is an optimum weight for a given type of hardware. Any attempt to decrease the weight below optimum would require additional cost through the use of exotic materials, additional manufacturing processes, or more complex fabrication techniques. By the same token, attempts to increase the weight above optimum would require additional cost for high performance propulsion, additional

structural analysis and testing, specialized tooling, et cetera.

Culture Variable. So far, it has been postulated that significant relationships exist among cost, quantity and weight. It is not likely, however, that the relationships are exactly the same for all different types of hardware. A situation, such as the one in Figure 3, may exist where the cost versus weight curves for several types of hardware have the same elasticity but different multipliers. The culture variable is defined as a value representing the vertical height of the cost/weight curve for a given subcategory of hardware. If the cost weight curves were plotted on a log-log graph, the lines would be parallel straight lines and the culture variable would be a function of the vertical intercepts.

A category is defined as a group of hardware systems that are functionally similar; such as, aircraft, ship, or spacecraft. A subcategory describes a group of systems that perform a similar mission or have the same oper-

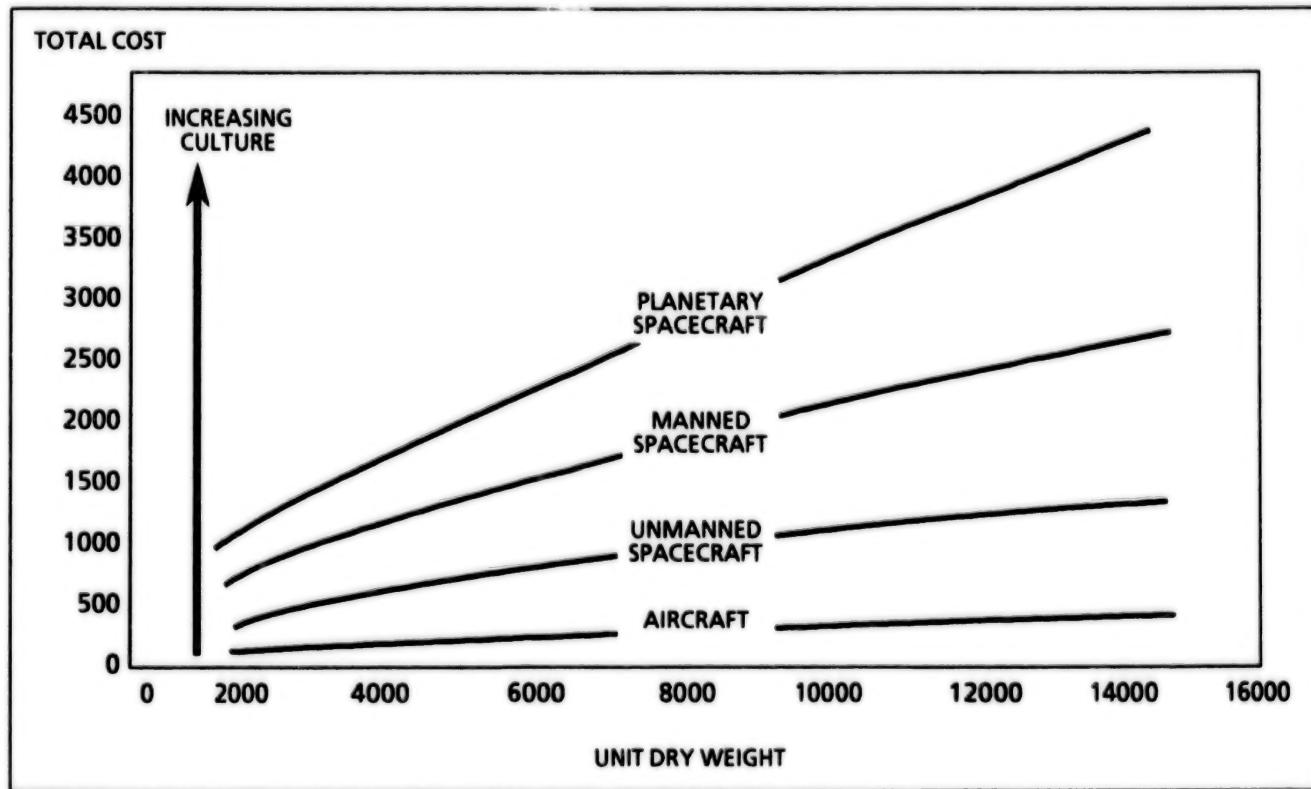


Figure 3. Culture Variable

ational environment. The subcategories of aircraft would include fighter, bomber, transport, etc. The classifications used in this paper are listed in Table 1.

It must be assumed, for the convenience of regression analysis, that the elasticities are the same for all subcategories. This will prove to be an overly restrictive assumption, and future work may focus on techniques to eliminate the need to make it.

Complexity Variable. Within a given subcategory, it is possible that the systems may vary considerably in terms of performance, capacity, level of technology, complexity of design, and many other factors. Variations of the type listed within a given subcategory are henceforth referred to by the variable name complexity. Complexity is obviously very difficult to define and quantify *a priori*.

The potential for overlap between culture and complexity can also create confusion. Research and development organizations tend to group along functional and mission lines; the classification scheme used for culture inherently contains organizational information as well. Organizational differences within a given subcategory may be included in complexity. Also, specification levels vary along the functional lines in platform, so only the specification differences within an established subcategory should be considered in complexity.

Since there is no readily available means of quantifying complexity *a priori*, this variable will not be used in the subsequent model derivation. It is discussed here in order to clarify the definition of culture and to provide a basis for future work to refine quantitative measures of complexity.

Table 1. Culture Classification Scheme

SUBCATEGORY	NO.	CULTURE	SUBCATEGORY	NO.	CULTURE
AIRCRAFT	63	1.82	SHIPS	29	1.14
ATTACK	8	1.96	A/C CARRIERS	5	1.11
BOMBERS	8	1.99	AMPHIB. ASSAULT	5	0.89
FIGHTERS	16	1.94	CRUISERS	4	1.19
FW-TRANSPORTS	10	1.63	DESTROYERS	5	1.25
PATROL	5	1.88	FRIGATES	3	1.14
ROTARY ATTACK	5	1.88	SUBMARINES	7	1.24
ROTARY CARGO	5	1.75	GROUND MOBILE	16	1.15
TRAINER	3	1.46	TANKS	4	1.24
COMMERCIAL	3	1.74	TRUCKS	7	0.82
MISSILES	87	1.89	APCs	2	0.96
AIR-AIR	13	2.04	RIFLES	3	1.59
AIR-ORBIT	1	2.04	SPACECRAFT	56	2.18
AIR-SURFACE	15	1.81	MANNED REENTRY	5	2.34
ANTI-TANK	4	1.78	MANNED ORBITAL	2	2.05
ICBM	11	1.92	PHYSICS & ASTRONOMY	12	2.20
SURFACE-AIR	12	1.97	EARTH OBSERVATION	6	2.04
SHIP-AIR	9	1.74	WEATHER	7	2.19
SURFACE-SURFACE, LAND	8	1.88	COMMUNICATION	9	2.22
SURFACE-SURFACE, OTHER	4	2.07	MISC. SPACE	2	1.95
ICBM (SUB)	4	1.89	PLANETARY	13	2.45
ROCKETS	6	1.64	UNMANNED REENTRY	7	2.04

Time Variable. Another factor that must be considered in estimating cost is the impact of time-related phenomenon. Inflation, productivity, technology and performance are just a few of the factors that may change with time. For most cost estimating applications, the effects of inflation are removed by applying standard inflation rates to convert the data to a constant-year dollars. The modeling of productivity, performance and technology change is not so easy.

Time-related phenomena may change at a fixed rate, like interest on a bond, or they may vary from one time period to another. The method of using a program milestone date as the time variable will result in a fixed rate of change when the model is estimated. Measurement of the variable rate case would require construction of an index, similar to an inflation index, and then selecting the appropriate index value based on the year of Initial Operational Capability (IOC), mid-point of construction or some other basis. A productivity or technology improvement index could be incorporated in this fashion. For this report, the IOC year was chosen to represent time.

Generation Variable. The design of a new aircraft, spacecraft or missile is often based on a previous design that has already been proven. A new airplane may use the previous airframe with only minor structural modifications. Spacecraft designs may use structural components, electronics, and mechanical systems already tested on a previous design. Designers may work with configurations they are familiar with from previous projects. The result may be considerable savings in the development cost of new hardware. Savings can also be achieved in production since the tooling already exists and manufacturing experience is far down the learning curve from the previous design.

In theory, the cost of each subsequent model should be considerably less than the previous

model. The amount of savings, however, would probably decrease as the series progresses. The total cost would be decreasing asymptotically to some level as shown in Figure 4.

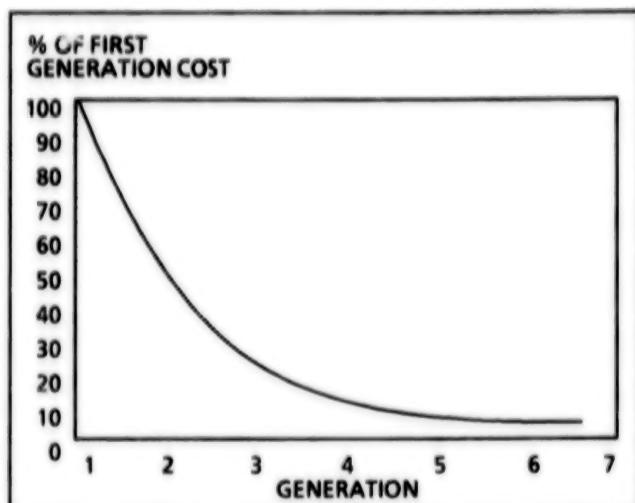


Figure 4. Generation Variable

The generation variable used in this paper is defined as the sequential number for a given model of a specific piece of hardware. Generation is not used to represent individual units of production, but rather a group of identical units. Subsequent generations must have very similar characteristics usually being produced by the same manufacturer or to the same specifications. Individual units of production may be given a generation number if they differ substantially from previous units but still retain the basic design and total production is small. All programs that do not have readily identifiable predecessors are given a generation of one.

Statistical Analysis

In order to statistically validate some of the theories relating to cost behavior, it was necessary to construct a database of cost and other variables for many different types of research and development programs. The database consists of 264 major programs. Most of the programs are U.S. Government sponsored. Many of the Government programs are defense-related weapons and delivery

systems. A substantial number of NASA sponsored spacecraft are also included. A small proportion of the data comes from other Government agencies, foreign countries and commercial companies. In total, the database represents \$1 trillion worth of expenditures in 1987 dollars.

Programs from the 1930s all the way up to the mid-1980s are included. Major categories include ground vehicles, ships, aircraft, missiles and spacecraft. Data collected for this study included top-level cost data, system weights, program schedule dates, developing organizations and technical data. A variety of sources were used to gather data, and information was confirmed by two or more sources whenever possible.

Model Evaluation. Model evaluation has consisted of three major steps. The first step was to test a model consisting of the variables quantity, weight, culture, IOC year and generation against the database as a whole. Step 2 required the estimation of

models for individual subcategories of data. Finally, the elasticities derived from step 2 were compared to the culture variable derived in step 1.

Step 1 had several major functions. One was to evaluate the theoretical model of quantity, weight, culture, IOC year and generation. A second function was to produce estimated values of culture for different program subcategories. A third purpose was to identify any data observations that may be incorrect or classified wrongly. The final function was to develop estimates for the elasticities of weight and quantity, as well as other presumed constants.

Using total program cost, weight, quantity and other data, a multiple linear regression analysis was performed. The results are presented in Table 2. Out of 264 data points, 253 observations were included in the regression model. The remaining observations were rejected due to missing data. The dependent variable is the log 10 of total cost. The inde-

Table 2. Regression Model Results

Dependent Variable: Log ₁₀ of Total Acquisition Cost			
Independent Variables:			
	COEF. VALUE	T-STAT	STD. ERROR
Constant	-4.7645		
Q Log ₁₀ Total Quantity	0.5773	47.5	0.0122
W Log ₁₀ Unit Dry Weight (lbs.)	0.6569	43.5	0.0151
C Culture	1.7705	31.8	0.0556
Y IOC Year - 1900	0.0124	9.3	0.0013
G Generation	-0.3485	-7.5	0.0466
Standard Error of Y Estimate	0.2247		
R Squared	0.9125		
Observations	253		
Degrees of Freedom	247		
MAPE	45%		
COST = 0.0000172Q	0.5773	W 0.6569	C 58.95
			Y 1.0291 G 0.4483

pendent variables are log 10, weight log 10, total quantity, culture, IOC year and generation. The coefficient of determination (R^2) is 0.91 and all of the variables are significant according to their statistics. Also, the signs and the magnitude of the coefficients are reasonable.

As discussed earlier, the culture variable is a derived value. The derivation begins by entering an estimated value for each culture subcategory. The multiple regression is performed using the original value for culture. The estimation errors for each subcategory is then adjusted by a factor calculated to make the average error for that subcategory zero.

A new multiple regression is then performed with the adjusted culture values. This process is repeated until the regression statistics stabilize. In order to minimize rounding errors, culture values are rounded at the second decimal place prior to the regression analysis.

A second regression analysis was done at the subcategory level for a few selected subcategories. This process generally used log 10 total cost as the dependent variable and log 10 weight and log 10 quantity as independent variables. In some cases, IOC year and generation were also included. The results of

step two are summarized in Table 3. Note that the R^2 values are good for almost all subcategories. The elasticity of weight and elasticity of quantity are displayed along with estimated culture values.

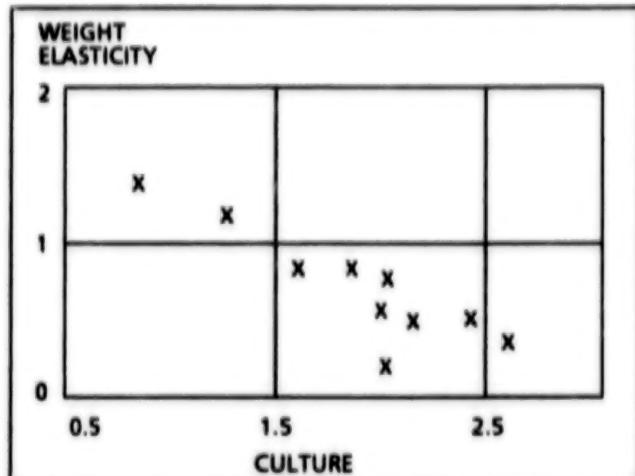


Figure 5. Weight Elasticity Versus Culture

The final step in the analysis was to compare the culture values to the elasticity values with respect to weight. Recall that culture is a function of the intercept of the regression lines and the elasticity is the slope of the regression lines in a log-log model. A regression analysis of the dependent variable weight elasticity and the independent variable culture found high correlation with an R^2 of 0.80, or 0.95 with the one outlier removed (see Figure 5).

Table 3. Subcategory Model Results

CAT	SUBCATEGORY	CULTURE	WEIGHT ELASTIC.	QUANTITY ELASTIC.	R ²
S/C	PLANETARY	2.52	0.45	1.02	0.87
S/C	PHYSICS & ASTRONOMY	2.31	0.68	1.17	0.95
MSL	AIR-AIR	2.06	0.69	0.53	0.86
MSL	ICBM	1.97	0.81	0.92	0.93
A/C	ATTACK	1.97	0.43	0.52	0.92
A/C	FIGHTER	1.96	0.74	0.46	0.95
MSL	AIR-GROUND	1.89	0.91	0.57	0.81
A/C	TRANSPORT	1.68	0.91	0.54	0.87
SHIP	SUBMARINE	1.33	1.18	0.92	0.99
SHIP	AMPHIB. ASSAULT	0.98	1.30	0.30	0.95

Furthermore, the coefficient of culture has a negative sign. This can be interpreted economically as meaning that high culture programs have greater economy of scale with respect to weight than low culture programs. Figure 6 illustrates the effect of the latter conclusion on the cost/weight curves. Note that moving down to the right increases the slope.

It is also noteworthy that two subcategories, submarines and amphibious assault ships, actually had weight elasticities greater than one, indicating diseconomies of scale.

An attempt was also made to correlate culture with quantity elasticity but the results were inconclusive. Of particular interest are the quantity elasticities of planetary, physics and astronomy satellites which are 1.02 and 1.17 respectively. The fact that these elasticities are close to or greater than one indicates that the marginal cost is constant or increasing. Since spacecraft generally have very small production runs, and the first few units are generally prototypes or test articles, this is not surprising. The high elasticities may

be indicative of the S-curve depicted in Figure 1d.

Model Validation. A procedure was developed for validating the statistically estimated model. At the time this paper was written, only the phase one total database model has been tested. The validation procedure consisted of dividing the database into two parts. The data was divided at the median IOC year, 1969. All programs prior to 1970 were used to calibrate a new model using the same variables as the overall model. Values for culture were also calibrated based on the limited data.

The restricted model was then used to simulate a forecast of the actual programs in the second half of the database. The result was that the simulated forecast overestimated the total actual cost by approximately 45%. This indicates a bias in the estimating model. An examination of the coefficients showed that all were reasonably consistent between time periods except for the coefficient of IOC year. The coefficient for IOC year is 50% higher in the first period than

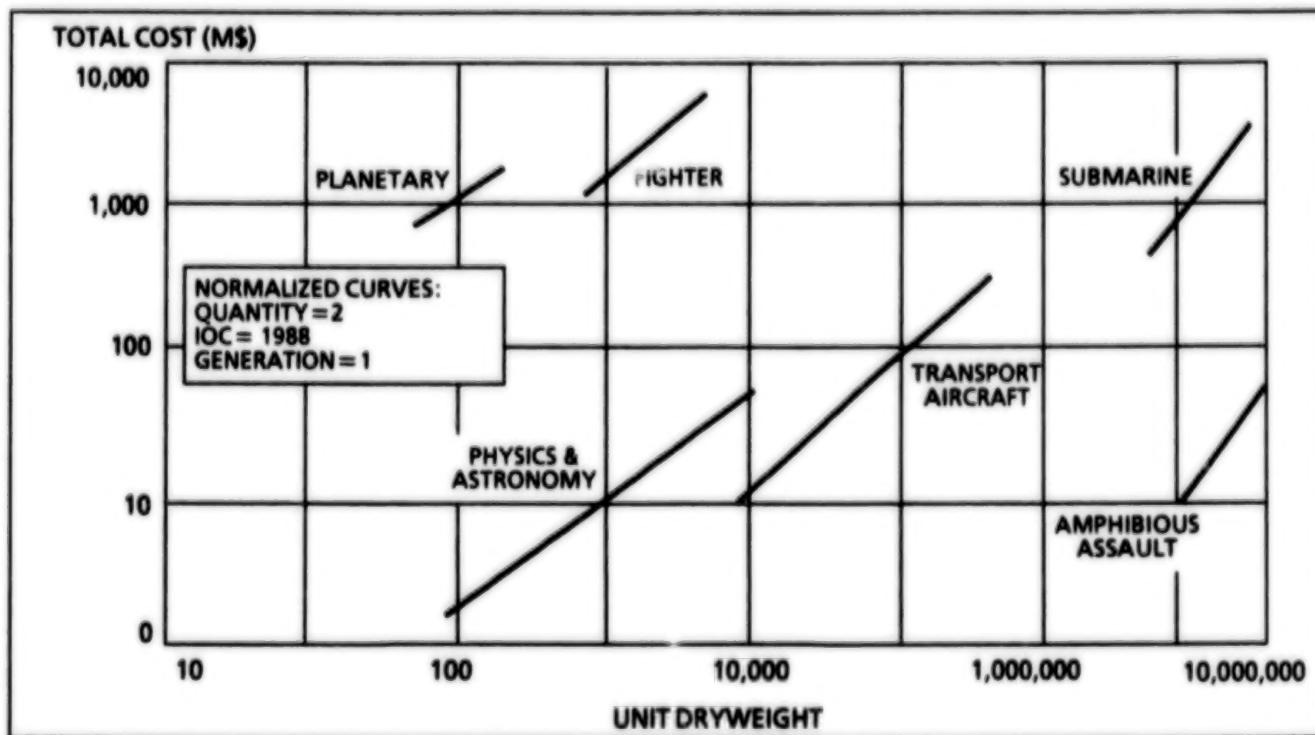


Figure 6. Subcategory Models

overall. This difference probably accounts for most of the overestimate. Several explanations may be offered for the variation in IOC year coefficients. Different inflation indices were used to normalize the data during different time periods. The indices used may not have been appropriate.

The IOC year variable used for time assumes a constant rate of change over the entire time period. It is possible that whatever factor the IOC year variable is attempting to measure was, itself, changing over time. Productivity changes in the work force are one possible explanation. Due to the magnitude of the error caused by the IOC year coefficient, it will be essential to identify the source of error before this model can be used for forecasting. Future work will focus on isolating the problem and developing solutions.

Conclusions

In order to accurately make any forecast using mathematical or statistical modeling, several conditions must be met. First, the structure of the model; i.e., the nature of the relationships, must be identified. Second, the parameters of the equation that are expected to vary, as input or outputs, need to be specified. Third, those factors that remain constant must be identified and estimated. Finally, the conditions under which the structural equations and parameters remain stable must be specified and tested. Only when thorough testing has indicated stability and accuracy over the expected range of forecasting requirements can a model be put to operational use.

The model identified in this paper is a fair predictor of general hardware development cost. As such, it proves that using many varied programs as a data base for estimating a cost model is a viable concept. The use of many data points from different technology domains has several advantages. First, it increases the number of degrees of freedom in

the statistical analysis which allows more explanatory variables to be used.

Second, the wider range of data available provides a deeper insight into the nature of the relationship between cost and various program factors. For example, a limited analysis of spacecraft data may have led to the conclusion that quantity elasticities are always greater than unity. In fact, production economies of scale should be achieved once the initial prototype stage is passed.

Third, a model based on a wide range of technologies should be more suitable for estimating the cost of new designs that may have no historical analogies. Finally, validating the model over different time periods may improve the confidence in estimates made far into the future. The model described here demonstrates that such a model can be constructed and will estimate cost within fairly reasonable bounds.

In addition, several economic conclusions can be drawn from the data model. The analysis shows that significant economies of scale with respect to weight exist for nearly all types of development hardware. The more complex the hardware, the greater the economies of scale. Also, the lower the weight of a subcategory, the greater the economies of scale are for that subcategory. Some classifications, such as ships, even have diseconomies of scale with respect to weight. The estimated elasticity of cost with respect to weight ranges from 0.43 to 1.30 with an average values of approximately 0.65. Economies of scale with respect to unit quantities also are evident. The range of estimated elasticities is very wide, from 0.3 to 1.17 with the average around 0.58. Some types of systems have diseconomies of scale. These are mostly very low production quantity systems such as spacecraft. The conclusion is that a modified learning curve such as Figure 1d may be appropriate.

The use of a culture variable was proven effective for combining different technologies in the same database. A methodology for deriving a quantitative measure of culture was presented and shown to produce good results. For future space developments, culture may be the most significant variable the cost analyst has to select. Weight and quantities will usually be given, but the particular hardware may not fall into any of the historical subcategories. It may also be possible to estimate culture for future programs using deterministic methods, such as a function of the ratio between weight and quantity. Another possible method of estimating new cultures would be interpolation or extrapolation of existing cultures.

The inclusion of a time-based variable causes the effects of time to be removed from the other variables in the model. The model could be used for long range planning if the future effect of time could be predicted. It was found that the cost of programs is increasing with time, even after the effects of inflation are excised. The time-related cost growth is not at a constant rate. The magnitude of cost growth appears to be from 0.0 to 3.0 percent per year. The exact nature of this time-related phenomenon is not yet understood, although it is believed to be combination of increasing performance, complexity and technology offset by improving productivity and development methods.

Finally, the benefits of design inheritance were clearly demonstrated. Substantial reductions in cost from using existing designs rather than starting from scratch are evident from the large negative coefficient of the generation variable. Cost savings of about 22 percent for each subsequent generation are predicted by the model. This fact has been used to great advantage on military acquisition programs and should be incorporated whenever possible in the space program.

The model does have some deficiencies. Most of the problems result from the wide range of estimated coefficients for subcategory models as shown in Table 3. The model of all data must effectively average these coefficients, which results in errors at the subcategory level. In addition, it was found that the modeling of time-related behavior (e.g., inflation, productivity, technology, etc.) is inaccurate. The model assumes that the rate change is constant but, in reality, it varies.

The combination of these two deficiencies makes the specified model unsuitable for long-range estimates of advanced space programs. Although the basic technique demonstrated here is sound, it must be refined even further to produce acceptable cost estimates. The specific weaknesses of the model have been identified and potential solutions will be implemented in the future.

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BUT WHAT WILL IT COST? THE HISTORY OF NASA COST ESTIMATING

by Joseph W. Hamaker

Within two years of being chartered in 1958 as an independent agency to conduct civilian pursuits in aeronautics and space, NASA absorbed either wholly or partially the people, facilities and equipment of several existing organizations. These included the laboratories of the National Advisory Committee for Aeronautics (NACA) at Langley Research Center in Virginia, Ames Research Center in California, and Lewis Research Center in Ohio; the Army Ballistic Missile Agency (ABMA) at Redstone Arsenal Alabama, for which the team of Wernher von Braun worked; and the Department of Defense Advanced Research Projects Agency (ARPA) and their ongoing work on big boosters.¹

These were especially valuable resources to jump start the new agency in light of the shocking success of the Soviet space probe Sputnik in the autumn of the previous year and the corresponding pressure from an impatient American public to produce some response. Along with these inheritances, there came some existing systems engineering and management practices, including project cost estimating methodologies. This paper will briefly trace the origins of those methods and how they evolved within the agency over the past three decades.

The Origins of the Art

World War II had caused a demand for military aircraft in numbers and in models that far exceeded anything the aircraft industry had even imagined before. While there had been some rudimentary work from time to time² to develop parametric techniques for predicting cost, there was certainly no widespread use of any kind of cost estimating beyond a laborious build-up of work hours and materials. A type of statistical estimating had been suggested in 1936 by T. P. Wright in the *Journal of Aeronautical Science*.³

Wright provided equations which could be used to predict the cost of airplanes over long production runs, a theory which came to be called the learning curve. By the time the demand for airplanes had exploded in the early years of World War II, industrial engineers were happily using Wright's learning curve to predict the unit cost of airplanes when thousands were to be built (and its still used today though the quantities involved are more likely to be hundreds instead of thousands).

In the late 1940s the Department of Defense and especially the U.S. Air Force were studying multiple scenarios of how the country should proceed into the new age of jet aircraft, missiles and rockets. The Air Force saw a need for a stable, highly skilled cadre of analysts to help with the evaluation of these alternatives and established the Rand Corporation in Santa Monica, California, as a civilian think tank to which it could turn for independent analysis. Rand's work represents some of the earliest and most systematic published studies of cost estimating in the airplane industry.

Among the first assignments given to Rand were studies of first and second generation ICBMs, jet fighters and jet bombers. While the learning curve was still very useful for predicting the behavior of recurring cost, there were still no techniques other than detailed work-hour and material estimating for projecting what the first unit cost might be (a key input to the learning curve equation). Worse still, no quick methods were available for estimating the nonrecurring cost associated with research, development, testing and evaluation (RDT&E). In the defense business in the early to mid-1950s, RDT&E had suddenly become a much more important consideration for two reasons. First, a shrinking de-

fense budget (between World War II and the Korean War) had cut the number of production units of most Air Force programs. Second, the cost of new technology had greatly magnified the cost of development. The inability to nimbly estimate RDT&E and first unit production costs was a distinct problem.

Fortunately, within Rand a cost analysis department had been founded in 1950⁴ under David Novick, who was drafted into the job because he was the only one around with any cost experience. This group at Rand proved to be prolific contributors to the art and science of cost analysis so much so that the literature of aerospace cost estimating of the 1950s and 1960s is dominated by the scores of Rand cost studies that were published.⁵ Novick and others at Rand deserve credit for developing and improving the most basic tool of the cost estimating discipline, the cost estimating relationship (CER), and merging the CER with the learning curve to form the foundation of aerospace estimating, which stands today.⁶

By 1951, Rand was devising CERs for aircraft cost as a function of such variables as speed, range, altitude, etc. Acceptable statistical correlations were observed at least acceptable enough for the high-level comparisons between alternatives that Rand was doing at the time. When the data was segregated by aircraft types (e.g., fighters, bombers, cargo aircraft), families of curves were discovered. Since each curve corresponded to different levels of complexity, the stratification helped clarify the development cost trends. Eventually, a usable set of predictive equations was derived that was quickly put to use in Air Force future planning activities.

The use of the CERs and stratification were basic breakthroughs in cost estimating, especially for RDT&E and first unit costs. For the first time, cost analysts saw the promise of being able to estimate relatively quickly and accurately the cost of proposed new systems.

Rand extended the methods throughout the 1950s and by the early 1960s the techniques were being acceptably applied to all phases of aerospace systems.⁷

The Early NASA Years

In the spring of 1957 the Army Ballistic Missile Arsenal (ABMA) in Huntsville, under the direction of Wernher von Braun, initiated design studies on a large and advanced rocket booster that could be used for large DoD payloads then being conceptualized.⁸ Numerous design options were under consideration and all of the most promising needed cost projections. Von Braun's team had long been flying experimental rockets, but precious little cost data existed, and none existed for the scale of the rockets that were coming off the drawing boards. Nevertheless, estimates were being demanded. With the procedures that Rand had used on aircraft, data was pieced together and plotted against gross liftoff weight because this performance variable was known both for the historical data points and for the concepts being estimated. The resulting CERs were at the total rocket level (engines being added separately based mainly on contractor estimates) and often did not inspire much confidence either by their correlation or their number of data points.⁹

Suddenly, in the fall of 1957 the Soviets launched Sputnik I and then, four weeks later, Sputnik II (carrying a dog), and the Army's big booster work took on an entirely new importance. While vehicle configuration studies inspired by the Soviet success continued at a rapid pace through 1958 and 1959, some momentous programmatic decisions were made regarding the ultimate management relationships between ABMA, the Army Redstone Project Arsenal (ARPA) and NASA. ABMA and von Braun, under ARPA sponsorship, were designing a massive rocket called Saturn. The DoD, however, as ARPA's parent organization, was coming to the conclusion that they did not need such a

super booster and was beginning to withdraw support over the objections of both ARPA and ABMA. In the end, by autumn of 1959, both the Secretary of Defense and President Eisenhower had concluded that ABMA and the Saturn should be transferred to NASA.¹⁰ In addition, a new home was found for the von Braun team by setting aside a complex within the borders of Redstone Arsenal in Huntsville.

By early fall of 1960, the Marshall Space Flight Center (MSFC) was operational.

NASA's first 10-year plan had been submitted to Congress in February 1960; it called for a broad program of Earth orbital satellites, lunar and planetary probes, larger launch vehicles and manned flights to Earth orbit and around the moon. The cost, estimated by analogies, intuition and guesses, was given as \$1 billion to \$1.5 billion per year.¹¹

With the Kennedy Administration in office by early 1961, planning for a manned lunar landing project continued. President Kennedy and Vice President Johnson were both interested in options for moving ahead of the Soviets, and NASA was working on plans that could place an American on the lunar surface shortly after the turn of the decade.

The orbiting of Yuri Gagarin in April 1961 caused immediate questions from the Administration and Congress about the costs of accelerating the plans. Jim Webb, the NASA Administrator, had been briefed on \$10 billion cost estimates associated with the moon project. Prudently, he decided to give himself some rope and gave Congress a \$20 to \$40 billion range. (The program was to cost about \$20 billion ultimately.)

Despite the magnitude of the cost projections, in his State of the Union address in May 1961, President Kennedy established his famous goal of a lunar mission before the

end of the decade. NASA was off and running. MSFC took responsibility for the Saturn launch vehicles, and the new Manned Spacecraft Center (MSC) in Houston, created in mid-1962 but operating before that out of Langley, was given responsibility for the payload—in this case the modules that would take the astronauts to the moon's surface and back.

While MSFC was being organized, the Jet Propulsion Laboratory (JPL) in California, in business as an Army research organization since the 1930s, was transferred to NASA from the Army. JPL had already built the Explorer satellite that had ridden an ABMA rocket into orbit as the country's first successful response to Sputnik. JPL began its association with NASA by being assigned the lead center role for Agency planetary projects. As JPL began designing several planetary probes, including the Ranger series of lunar spacecraft, the planetary series of Mariner spacecraft and the Lunar Surveyor spacecraft, they were dependent primarily upon contractor quotes for purchased hardware and their own work-hour and material estimates for inhouse work.

As the pace of planning picked up, they began to use an Air Force tool, the *Space Planner's Guide*,¹² a chapter of which is devoted to weight-based CERs for space project estimating. In 1967, Bill Ruhland, a former Chrysler Saturn I-C manager, went to work at JPL and contracted with a new company called Planning Research Corporation (which had been started by some former analysts who had worked on the *Space Planner's Guide*) to improve the CERs.¹³ Ruhland stuck with estimating, and went on to become NASA's preeminent estimator for planetary spacecraft throughout the 1970s and 1980s. PRC leveraged its early relationship with JPL and Ruhland by establishing cost modeling contracts with most of the other NASA centers and dominating the development of NASA cost models for the next 25 years.

In March 1961, with launch vehicles, manned capsules and planetary spacecraft work underway, NASA dedicated the Goddard Space Flight Center (GSFC) as another development center. GSFC was assigned responsibility for Earth orbital science satellites and soon had on the drawing board a number of spacecraft for which cost estimates were needed. The Orbiting Astronomical Observatory, the Orbiting Geophysical Observatory and the Nimbus programs were all started early in the 1959-60 period and, like most other projects in the Agency at the time, experienced significant cost growth. GSFC organized a cost group to improve the estimates, first under Bill Mecca, and later managed by Paul Villone. In 1967 Werner Gruhl joined the office where he implemented numerous improvements to the GSFC methods. In later years he joined the Comptroller's office at NASA Headquarters as NASA's chief estimator.

Among the improvements creditable to GSFC during the late 1960s and early 1970s were: 1) spacecraft cost models that were sensitive to the number of complete and partial test units and the quality of the test units; 2) models devoted to estimating spacecraft instruments; and 3) the expansion of the database through the practice of contracting with the prime contractor to document the cost in accordance with NASA standard parametric work breakdown structures (WBS) and approaches.¹⁴

By 1965 most of NASA's contractors were revising their traditional approach to cost estimating, which had relied upon the design engineers to estimate costs, replacing it with an approach that created a new job position that of trained parametric cost estimators whose job it was to obtain data from the design engineers and translate this information into cost estimates using established procedures.¹⁵ At essentially the same time, cost estimating was being elevated to a separate discipline within NASA Headquarters and at

the NASA field Centers. This trend toward cost estimating as a specialization was caused by several factors. First, it was unrealistic to expect that the design engineers had the interest, skills and resources necessary to put together good cost estimates. Second, during the preceding three years, the pace of the Gemini and Apollo programs had so accelerated that the Requests for Proposals issued by the government typically gave the contractors only 30 days to respond—only parametricians had any hope of preparing a response in this short amount of time. Third, because of growing cost overrun problems, NASA cost reviews had increased notably and the reviewers were looking for costs with some basis in historical actuals—essentially a prescription for parametric cost estimating.

At both MSC and MSFC, the cost estimating function was placed in an advanced mission planning organization. At MSC, it was embodied within Max Faget's Engineering and Development Directorate,¹⁶ and at MSFC it was within the Future Projects Office headed by Herman Koelle.¹⁷ Faget, an incredibly gifted engineer, had already left his imprint on the Mercury, Gemini and Apollo programs, and was a strong believer in an advanced planning function with strong cost analysis. Koelle, a German engineer who, though not a member of the original team, had later joined von Braun, was also extremely competent and very interested in cost. Koelle had, in fact, along with his deputy William G. Huber, assembled the very first NASA cost methodology in 1960, published first in an inhouse report¹⁸ and then in 1961 as a handbook that Koelle edited for budding space engineers.¹⁹

Out of the eye of the Apollo hurricane for the moment, both the MSFC and the MSC cost personnel now sought to regroup and attempt to make improvements in capability. In 1964 MSFC contracted with Lockheed and General Dynamics²⁰ to develop a more rigorous and sophisticated cost modeling capabil-

ity for launch vehicle life cycle cost modeling. This effort was led by Terry Sharpe of MSFC's Future Projects Office. Sharpe, an Operations Research specialist interested in improving the rigor of the estimating process, led the MSFC estimating group as they managed the contractors' development of the model and then brought it inhouse and installed it on MSFC mainframe computers.

Through about 1965 the only computational support in use by NASA estimators was the Freidan mechanical calculator. By the mid-1960s mainframe time was generally available, and by the late 1960s the miracle of hand-held, four-function electronic calculators could be had for \$400 apiece—one per office was the general rule. Throughout the early 1970s the hand-held calculator ruled supreme. By the middle 1970s, IMSAI 8080 8-bit microcomputers made their appearance. Finally, by the late 1970s the age of the personal computer had dawned. Estimators, probably more than any other breed, immediately saw the genius of the Apple II, the IBM PC and the amazing spreadsheets: Visicalc, Supercalc and Lotus 1-2-3. Civilization had begun.

The resulting capability was extremely ambitious for the time, taking into account a multitude of variables affecting launch vehicle life cycle cost. The model received significant notoriety, and once the CIA inquired if the MSFC estimators might make a series of runs on a set of Soviet launch vehicles. Busy with their own work, the estimators demurred. The CIA pressed the case to a higher level manager, a retired Air Force colonel. Suddenly the MSFC estimators discovered that they had been mistaken about priorities. The runs were made and the CIA analysts went away happy.

Later in 1964 after a reorganization, management of the MSFC cost office was taken over by Bill Rutledge who went on to lead the MSFC cost group for more than 20 years.

Rutledge steadily built the MSFC cost group's strength until it was generally recognized in the late 1960s as the strongest cost organization within the Agency. One of Rutledge's more outstanding innovations was the acquisition of a contractor to expand and maintain an Agencywide cost database and develop new models. The REDSTAR (Resource Data Storage and Retrieval) database was begun in 1971 and is still operational today, supporting Agencywide cost activities. The contract was originally awarded to PRC and, under Rutledge's management, developed numerous models throughout the 1970s and 1980s.

MSFC also established a grassroots cost estimating organization within the MSFC Science and Engineering laboratories. This group was managed by Rod Stewart for a number of years. After his retirement from NASA, Stewart, along with his wife Annie, authored an outstanding series of cost estimating books.²¹ In 1966, MSC, working in parallel to the MSFC activities, contracted with General Dynamics²² and Rand²³ to improve their spacecraft estimating capability. The MSC cost group also significantly improved their capabilities during this period under the able management of Humboldt Mandell, who was later to play a leading role in the Shuttle, Space Station and Space Exploration Initiative cost estimating activities.

By 1967 both the MSC and MSFC cost estimating organizations were beginning to obtain the first historical data from the flight hardware of the Apollo program. This included cost data on the Saturn IB and Saturn V launch vehicles by stage, and on the Command and Service Module (CSM) and the Lunar Excursion Module (LEM) at the major subsystem level. Fairly shallow data by today's standards, it was considered somewhat of a windfall to the NASA estimators who had been struggling along with two- and three-data point CERs at the total system

level. The Project Offices at MSC and MSFC compiled the data between 1967 and 1969 and documented the results in the unpublished Apollo Cost Study (preserved today in the JSC and MSFC cost group databases). Eventually this was supplemented by paying the CSM prime contractor to retroactively compile the data in a WBS format useful for parametric cost estimating.²⁴ Despite these improvements, one Rand report in 1967 laments that the number of data points for cost estimating was depressingly low... "only one subsystem contains more than four data points and this paucity of data precludes the application of statistical techniques either in the development of the CERs themselves, or in the establishment of confidence levels for the predictive values generated by the CERs."²⁵

While most of the science programs were managed out of JPL and GSFC, the research centers (Ames, Langley, and Lewis) were also given development projects from time to time. Ames managed the Pioneer planetary probes, Langley managed the Lunar Orbiter and the Viking Mars mission, and LeRC managed the Centaur project. Generally, the costs were estimated using models from the other Centers.

The Shuttle Era: Promise of Low Cost

By 1968 the nation was immersed in social and political turmoil, the Vietnam War and the attempt to build the Great Society. Though the accomplishment of the first manned lunar landing was not to occur until the following year, the budget that NASA received was lower than the previous year and broke the trend of ever increasing flows of money that the Agency had enjoyed since its creation a decade before. NASA realized that the dream of building directly on the expendable Saturn launch vehicle technology, building Earth orbital and lunar orbital space stations, continuing exploration of the lunar surface and mounting an expedition to Mars were not in the immediate plans.

By early 1969, while the ongoing Apollo program prepared for the Apollo 11 mission to the moon on which humans would land for the first time, future planning activities within NASA had been scaled back from the overly ambitious, broad set of space activities to focus on the crucial next step. Space stations, moon bases and Mars missions all needed low-cost, routine transportation from the Earth's surface to low Earth orbit. If the budget realities precluded doing everything at once, then the next thrust would be in low Earth orbit transportation as a first building block to all the rest.

A task force was assigned in March 1969 to study the problem and recommend options for further study.²⁶ This report called for the development of a new space shuttle system that could meet certain performance and cost-per-flight objectives. Many options were examined, but the fully reusable two-stage was the preferred choice because it seemed to offer the lowest recurring cost. Concurrently with these inhouse assessments, four parallel Phase A (i.e., conceptual design) studies had been awarded to General Dynamics, Lockheed, McDonnell Douglas and North American (today's Rockwell International). For most of 1969 these studies proceeded apace, churning out massive stacks of paper designs, along with cost numbers that gave the impression that all was well. For around \$10 billion in development costs, the most reusable Shuttle configurations offered recurring costs of only a few million dollars per flight.

As the Phase A studies neared completion in late 1969, however, two cost-related problems began to emerge. First, NASA's communications with the Office of Management and Budget (OMB) revealed that the outlook for the NASA budget was not good. The projections showed that continued reductions in NASA's funding were inevitable; the lower budget numbers did not match the amount needed to fund the favored Shuttle designs.

Second, as NASA reviewed the contractors cost estimates for the Shuttle and compared the numbers to their own estimates, it became clear that no one in the industry or the government had a good handle on what the Shuttle could be expected to cost.²⁷

The problem with the estimates was analogous data. A winged, reusable spaceship had never been built before and all the cost estimates were being based on extrapolations from large aircraft such as the C-5, B-52, B-70 (for wings, fuselage, landing gear, etc.), from the Saturn (for tanks, thrust structure, etc.) and from the Apollo capsules (for crew systems). The problem was compounded by the scope of the estimating job. All the various designs being contemplated overloaded the estimating resources that NASA had at the time. The entire complement of NASA estimators at the two lead Centers (JSC and MSFC) numbered only eight people, yet cost was to be one of the most key variables in the decision making process concerning the Shuttle.²⁸

Because the magnitude of the upfront costs of the fully reusable systems had not yet been adequately estimated, NASA proceeded into Phase B in mid-1970 with the intent of putting more meat on the bones of the skeletal designs. Meanwhile, negotiations with the Office of Management and Budget continued concerning the budget outlook, and the numbers got lower and lower. Slowly, the cost estimates became more realistic just as the Phase B studies were nearing completion in the summer of 1971.

The studies were extended so that cost cutting measures could be investigated. First, expendable drop tanks were substituted for reusable interior tanks. Then the flyback booster was scrapped, first for expendable liquid rocket boosters, then for expendable solid rocket boosters. Taken together, these reductions made it possible to barely fit the Shuttle's development within the OMB

guidelines, but each change had added to the recurring cost per flight.²⁹

But the Shuttle peak year funding versus the OMB budget cap was not the only cost question dogging the Shuttle. For the mandated Mercury, Gemini and Apollo programs, money had flowed without any requirement for the Agency to show economic justification for the projects. When the idea of a Shuttle system was floated in 1969 as part of NASA's plans after Apollo, the OMB decided that such an expensive undertaking ought to show some economic benefits that outweighed the costs. Because the analytical skills for an economic justification did not exist inhouse and NASA thought it wise to have independent support for the Shuttle, the Agency hired the Aerospace Corporation, Lockheed and economist Oskar Morgenstern and his company Mathematica to develop the data OMB wanted to see. Morgenstern turned the economic analysis over to a young protege named Klaus Heiss. Heiss put together an impressive study³⁰ that compared the life cycle costs of the Shuttle with the costs of the equally capable expendable launch vehicles.

One of the more important arguments for the Shuttle case was that payloads on the Shuttle would cost considerably less than payloads on expendables, a notion that was based on an extensive cost estimating study done for NASA by Lockheed.³¹ This study, a classic for its scope, originality and methodology, nevertheless reached an exactly wrong conclusion.

It is known now that Shuttle payloads actually cost more than those that fly on expendable launch vehicles due to the strenuous safety review process for a manned vehicle. But Lockheed forecasted that the payload developers would save about 40 percent of their costs from the advantages offered by the Shuttle. The advantages were thought to be that: 1) the relatively high weight lifting per-

formance and payload bay volume offered by the Shuttle would allow payloads to ease up on lightweighting and miniaturization, which are cost drivers; 2) the Shuttle would allow retrieval and refurbishment of satellites instead of buying additional copies as was necessary with expendable rockets; and 3) a single national launch system such as the Shuttle would allow standardization of payloads instead of multiple designs configured for the plethora of expendable vehicle interfaces. Finally, it was Aerospace's job to determine the payload requirements and produce traffic models, and they ultimately forecasted the need for 60 Shuttle flights per year.³² While the Shuttle payload benefits and flight rates were both flawed assumptions, Klaus Heiss constructed a discounted cost benefit analysis that asserted savings in the billions. At the least, the Aerospace, Lockheed, Mathematica work sent the OMB accountants to murmuring.

President Nixon finally gave the nod, and the Shuttle's detailed design began in the summer of 1972 under contract to the winning prime contractor, North American—though this did not end the debate over the worthiness of the project.³³ All through 1973 NASA was very involved in extensive capture/cost analyses to produce data to answer Congressional, GAO and OMB inquiries about the Shuttle's economic forecasts. These analyses were NASA inhouse extensions of the work done by Mathematica, Lockheed and Aerospace. The studies consumed most of the resources of the MSFC and JSC cost groups as well as Headquarters program office personnel. They compared the discounted life cycle costs of capturing the NASA and DoD payloads with the Shuttle versus expendable launch vehicles. The Shuttle case was finally determined to yield a 14 percent internal rate of return and \$14 billion of benefits (in 1972 dollars). This data was used as the final reinforcement of the Shuttle program commitment.

Declining Budgets, Rising Costs

Once Shuttle development was safely underway by 1974, most of the estimating talent of the Agency was turned to various kinds of scientific satellite estimating. As NASA's budget declined in the 1970s, both JPL and GSFC pioneered such economies as the use of the protoflight concept in spacecraft development. Before the 1970s NASA had prototyped most spacecraft (i.e., built one or more prototypes which served as ground test articles) before building the flight article. In the protoflight approach, only one complete spacecraft is built, which serves first as the ground test article and is then refurbished as the flight article. The protoflight approach theoretically saves money. However, these savings must be balanced against the cost of refurbishing the test article into a state ready for flight, the cost of maintaining more rigid configuration control of the ground test article to insure its eventual flight worthiness, and the increased risk of having less hardware.

Other attempts were made to lower cost without much success. Low estimates based on wishful thinking concerning off-the-shelf hardware and reduced complexity proved unrealistic, and overruns began to breed more overruns as projects underway ate up the funds other projects had expected.

Meanwhile, as NASA Headquarters continued to guide the overall programs, handle the political interfaces, foster other external relations, and integrate and defend the Agency budget, a need was seen to strengthen the Washington cost analysis function.³⁴ Having moved to the Headquarters Comptroller's Office from GSFC in 1970, Werner Gruhl set up an independent review capability under Mal Peterson, an assistant to the Comptroller. Gruhl aggressively championed the constant improvement of the database. Gruhl and Peterson's greatest contribution was probably their relentless urging for real-

istic estimates. They also initiated an annual symposium for all NASA estimators and were instrumental in helping to establish a process for Non-Advocate Reviews (NARs) for potential new projects.

The NAR was instituted as a required milestone in which each major new project had to prove its maturity to an impartial panel of technical, management and cost experts before going forward. As part of the NAR process, Peterson and Gruhl, working with a relatively small staff of one to three analysts, undertook to perform independent estimates of most of the major new candidates for authorization. Peterson largely devoted himself to penetrating reviews of the technical and programmatic readiness, the underpinning of the cost estimate. Gruhl, using mostly models of his own developed from the RED-STAR database, generated his own estimates. Together they were a formidable team and undoubtedly reduced the cost overrun problem from what it would have been without the NAR.

Another significant milestone in cost estimating that occurred during the 1970s was the emergence of the Price Model. First developed within RCA by Frank Freiman, the model began to be marketed in 1975 by RCA as a commercially available model. Freiman's brainchild was arguably the single most innovative occurrence in parametric cost estimating ever. His genius was to see hardware development and production costs as a process governed by logical interrelationships between a handful of key variables. Probably feeling his way with intuition and engineering experience more than hard data, Freiman derived a set of algorithms that modeled these relationships. The resulting model could then be calibrated to a particular organization's historical track record by essentially running the model backward to discover what settings for the variables gave the known cost. Once calibrated, the model could be run forward using a rich set of tech-

nical and programmatic factors to predict the cost of future projects. While the Price models are applicable to a wide range of industries in addition to aerospace, the model first found use in the aerospace industry. NASA encouraged Freiman to market his invention, and actually provided him with data for calibrating the model after observing its potential in Shuttle cost estimating.³⁵ The success of the Price model inspired the development of several other commercial cost models with application to hardware, software and the life cycle.

By the late 1970s and into the mid-1980s, the cost of NASA projects was a serious problem. It was now obvious that Shuttle payloads cost more, not less, than payloads on unmanned vehicles. Overruns were worse than ever despite better databases, better models, better estimators, and more stringent Headquarters reviews. It seemed that NASA was in danger of pricing itself right out of business.³⁶ At JSC, Hum Mandell, assisted by Richard Whitlock and Kelley Cyr, initiated analyses of this problem. Making imaginative use of the Price model,³⁷ they found that NASA's culture drives cost and that the complexity of NASA projects had been steadily increasing, an idea also advanced by Gruhl. Mandell argued persuasively to NASA management for a change in culture from the exorbitantly expensive to the affordable. At the same time, he argued that estimates of future projects needed to account for the steadily increasing complexity of NASA projects.

Recent Years

Once the Space Shuttle had begun operations, NASA turned its attention once again to defining a Space Station. After Pre-Phase A and Phase A studies had analyzed several configurations, in 1983 NASA ran a Washington-based, multi-center team called the Configuration Development Group (CDG) to lead the Phase B studies. The CDG was led by Luther Powell, an experienced MSFC project manager. For his chief estimator, Powell

chose O'Keefe Sullivan, a senior estimator from the MSFC cost group. Sullivan had just completed managing the development of the PRC Space Station Cost Model,³⁸ an innovative model that created a Space Station WBS by cleverly combining historical data points from parts of the Shuttle Orbiter, Apollo modules, unmanned spacecraft and other projects. This model was distributed and used by all four of the Work Package Centers and was probably the most satisfactory parametric cost model ever developed by NASA. Work Package 1 (WP-1) was at MSFC, with responsibility for the Station modules; WP-2 was at JSC with responsibility for truss structures, RCS and C&DH; WP-3 was at LeRC with responsibility for power; and WP-4 was at GSFC with responsibility for platforms. Sullivan used the model to estimate the project at between \$11.8 and \$14 billion (in 1984 dollars). The content of this estimate included the initial capability, eight-person, 75-kilowatt station and space platforms at two different orbital locations, with additional dollars required later to grow the program to full capability.³⁹

Meanwhile, NASA Administrator Jim Beggs had been negotiating with the OMB for support to start the project. Under pressure to propose something affordable, Beggs committed to Congress in September 1983 that a Station could be constructed for \$8 billion, a rather random number in light of the known estimates and the fact that the conceptual design had never settled down to an extent necessary for a solid definition and cost estimate. Nevertheless, the Agency pushed ahead with the Phase B studies and by fall 1987, needing to narrow the options in configurations still being debated between the Centers, established a group called the Critical Evaluation Task Force (CETF), quartered at LaRC and led by LaRC manager Ray Hook. Hook brought Bill Rutledge in from MSFC to lead the cost analysis effort, and Rutledge assembled a team made up of estimators representing the Work Package Cen-

ters and Headquarters (Bill Hicks, Richard Whitlock, Tom LaCroix, and Dave Bates). Over a period of a few intense weeks, they generated the cost of the new baseline, which, even after significant requirements had been cut, still totaled at least \$14 billion.

NASA reluctantly took this cost to the OMB. Seeking to inspire a can-do attitude among the CETF team, NASA management passed out buttons containing the slogan We Can Do It! One senior estimator, who had seen it all before, modified his button to read We Can Do It For \$20 Billion!⁴⁰ Amid great political turmoil, the Space Station was finally given a go-ahead. Despite contractor proposed costs that were more unrealistically optimistic than usual, the source evaluations were completed and contracts were awarded for the four work packages. The project managed to survive several close calls in the FY1988 through FY1991 budgets, though with steadily escalating costs and several iterations of requirements cutbacks and redesigns. Like the purchase of a car, the sticker price includes nonrecurring cost only, and this is the cost NASA had always quoted Congress for new projects, including the Space Station. During the long and winding road of gaining Congressional authority for the Station, NASA was asked to include other costs such as Station growth, Shuttle launch costs, operations costs, and various other costs, which led to confusion and charges of even more cost growth than actually occurred.

As this is being written, NASA is actively designing and estimating the cost of several major future programs including the Earth Observation System, the National Launch System and the Space Exploration Initiative, among others. Each of these programs, like most NASA programs before them, is unique unto itself and presents a new set of cost estimating challenges. At the same time, the recent years of growth in budget resources that NASA has enjoyed seems to have run its course. In an era of relatively level budget

authority, NASA is seeking ways to maximize the amount of program obtainable. New ideas on this topic abound. Total Quality Management, Design to Cost, Concurrent Engineering and a number of other cultural changes are being suggested as a solution to the problems of high cost. As usual, the NASA estimating community is in the middle. Armed with data from the past, which somehow must be adapted to estimate the future, they attempt to answer the all important question: But what will it cost?

So brief a treatment of the history of NASA cost estimating leaves so much unsaid that apologies are in order. Nothing was mentioned of the aeronautical side of NASA, yet they estimate the cost of projects that are no less important to the nation than the space

projects focused upon here. The Kennedy Space Center facilities and operations costing was not mentioned, though nothing NASA has sent to space could have been sent without them. Whole projects from which much was learned about cost estimating (Viking, Skylab, Spacelab, Centaur-G, Hubble Space Telescope, Galileo, Magellan, Ulysses and many others) had to be left unexplored. Even when touched upon, many subjects were given only the barest of treatments, the expansion left for other studies.

Finally, while this paper unfairly singles out a dozen or so individuals, another few score men and women who have labored hard in the crucial and controversial business of NASA cost estimating will not see their names here. They are saluted anyway.

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IMPROVING COST EFFICIENCY IN LARGE PROGRAMS

by John D. Hodge

This paper examines the question of cost, from the birth of a program to its conclusion, particularly from the point of view of large multi-center programs, and suggests how to avoid some of the traps and pitfalls. Emphasis is given to cost in the systems engineering process, but there is an inevitable overlap with program management. (The terms systems engineering and program management have never been clearly defined.) In these days of vast Federal budget deficits and increasing overseas competition, it is imperative that we get more for each research and development dollar. This is the only way we will retain our leadership in high technology and, in the long run, our way of life.

One of the most vexing aspects of managing large programs within NASA (or any other high technology government programs) is how to allocate program funds in a way that is best for the program. One of the major reasons is that the role of cost changes throughout the phases of the program. Another reason is that total cost is not all that easy to define; yet another is that funding, which is based on annual appropriations, is almost never consistent with fiscally efficient program spending rates. The net result is that program costs almost always escalate and inordinate time is spent controlling costs at the expense of maintaining performance or schedule.

Many studies have tried to address this problem. They show that program costs will escalate by at least a factor of three, from approval to completion. The studies suggest a number of guidelines that should be followed if costs are to be kept down, including clear definition of requirements, stable management and strong central control. Unfortunately, these factors are not always under the control of the program manager.

The principles are simple. First, define very carefully what it is you are trying to do. Check everything you do against that baseline, even if it has to be changed, and resist change once the decisions have been made. Second, break up the program into manageable sized deliverables that can be measured in terms of cost, schedule and performance, and define the interfaces between them. Third, continuously assess the risks to success as the program proceeds, and modify only as necessary.

Requirements Traceability

Most studies have shown that the primary reason for cost escalation is that not enough time or resources are spent in defining the program. It is clear that you cannot control what you have not or cannot define. It is during this period that some of the most elegant systems engineering should be performed, especially in understanding the cost of every requirement and its systems implication. Even if the definition is adequate during the early phases of the program, it is imperative that great vigilance be exercised in maintaining the baseline definition of the program and the fundamental reasons for doing the program.

This process establishes a small but influential part of the program office, preferably within the systems engineering organization. The program office must be dedicated to the traceability of requirements and to ensuring that a clear path exists from program rationale to program requirements to systems requirements to systems design. Too often, once a design has been established, changes are proposed and enacted that bear little relationship to the original premises of the program. As will be discussed later in this paper, there are many reasons for change, but where possible, changes should

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be considered during the formulation of the program and not later when the program structure is in place and the program is in progress. Change is almost always costly; requirements traceability provides a bulwark against which the program manager and the systems engineer can stand and defend.

Baseline Cost, Schedule and Performance

The three main parameters in the control process—cost, schedule and performance—are the program manager's bread and butter. Again, program definition is vital and necessary from the very beginning. It may be argued that clear definition is not possible, particularly early in the program; nevertheless, an approved, traceable baseline, although it may alter, must be known at any given time, and must include everything in the program. The "I forgots" can kill you. The key to success in handling these three parameters is to manage the balancing act between them. Cost, schedule and performance are usually dependent variables and at various times, one or another may assume greater or lesser importance. A single variable, however, should never be changed without knowing the impact on the other two. Within the NASA culture, performance is generally the predominant factor, and schedule is a distant second. Cost tends to be considered mostly in the context of the annual appropriation, but from the point of view of the program manager, all three parameters must be defined and approved continuously, which is a function of the systems engineering process.

Program Risk Analysis

In recent years, especially since the Challenger accident, program risk analysis has come to be used largely in the context of crew safety, but this is only a part of program risk. Basically, program risk analysis assesses the probability of meeting requirements as changes occur. A number of analytical tools now available can be used to under-

stand the relationships between cost, performance and schedule. Again, a small group within the systems engineering organization should be dedicated to understanding the impact of any change on all three parameters. Armed with this information, risk can be reduced in many ways. Adding more money, reducing the performance requirements, or extending the schedule are most often used. A competent systems engineer will know the relationships between these three variables and the impact of any situation on the total program.

The Role of Cost in Phased Procurement

The most common form of procuring high technology capability within the Federal Government is known as phased procurement. The theory behind this procurement method is that commitment to the program gradually increases with time and in discrete stages. Within NASA, there are four standard phases; others are beginning to creep in as the ability to establish new programs becomes more difficult and the duration and cost of operations becomes a more significant part of total program costs. The role of cost is different in each of the phases. The phases are:

Pre-Phase A: This is a very unstructured period that examines new ideas, usually without central control and mostly oriented toward small studies. This period can last for a decade or more and produces the list of ideas and alternatives from which new programs are selected.

Phase A: Sometimes called the feasibility phase, this is a structured version of the previous phase. Usually a task force or program office is established, and multiple contracts will be awarded. The goal of this phase, which may last for several years but usually is limited to one or two years, is to decide whether a new program will be started and what its purpose and content should be. This phase repre-

sents less than one percent of the total program costs. Nevertheless, it is largely a systems engineering effort and sets the stage for everything that follows.

Phase B: Sometimes known as program definition, this phase is the most important in establishing the basic parameters of the program. By the time this phase is finished (a period of two or three years), the program rationale, cost, schedule, performance, management style and the most likely technical solution will have been established. This phase usually involves multiple contracts to establish a variety of ideas and a competitive environment, should the program proceed. Cost is continuously assessed as a function of design solutions relative to basic requirements. Studies indicate that from five to ten percent of the total program costs will need to be expended if control is to be maintained over the program during Phases C and D.

Phase C/D: Originally separate phases, this period covers design, development, test and evaluation. Contracts may be open to all qualified bidders or only to those involved in the previous phase. Although competition is not usually open between Phases C and D, commitment to Phase D depends on a successful and acceptable design. In past programs, two-thirds of the total program cost was expended during this period. The systems engineering role has begun to shift toward systems specification and systems interfaces. The secret to cost control is a sound definition of end items and their interfaces with a tight hold on changes.

Phase E: In most past programs, the operations costs were less than 20 percent of the total cost. This was because there was a definite end to a relatively short-term program. In recent years, particularly in the manned programs, the length of the

operational phase has increased significantly. In the case of the Shuttle, it could be conceived as indefinitely long. For this reason, life cycle costs should be a major consideration from the beginning.

Selling the Program

The definition of a new start within NASA varies by program and organization but can generally be said to occur at the beginning of Phase B. Prior to that time, the program manager is selling the program. The total expenditure of funds during the selling period is usually far less than one percent of the final program costs; this is, however, when the basic parameters of the program are established. It is a time of building constituents both inside and outside the Agency. Assuming that a feasible technical solution is available and an acceptable management scheme can be provided, much of the debate about whether a program should be approved centers largely around the question of cost. Of course, with only preliminary designs available, only cost estimates can be made and these are obtained from standard cost models.

Cost Estimating

During Phase A of the program, when the most rudimentary designs are available, it is essential that program cost estimates are made before the program start can be authorized. Estimates are made using cost models that have been developed on the basis of past experience on similar programs. These models are among the most arcane devices invented by engineers, so a few words on how they work are appropriate.

Past experience is captured by documenting the cost of each system on the basis of weight. Regression analysis is performed to determine a straight line log relationship. Once the weight of the system has been estimated, the cost can be determined. This estimate is multiplied by a complexity factor to allow for the risk associated with the select-

ed technology and may vary from as little as 0.50 to 2 or more. This is repeated for each system, and the total becomes the baseline cost. This total is multiplied by a factor to allow for systems engineering and testing by the prime contractor. This is known as the "prime wrap" factor and is again determined based on all relevant past experience.

All prime contractor estimates are added and then multiplied by a second factor known as the "nonprime wrap." This is the cost of government work. Finally, a reserve factor is used to allow for problems during the program. There are separate cost models for manned and unmanned programs, which are significantly different. In general, for the unmanned programs, about 40 cents of every dollar goes to hardware, and in the manned programs, about 20 cents.

These cost models pose a great many problems. First, they are normalized on the basis of weight. Clearly this is not valid in all cases, particularly structure. Second, they do not explain why the costs are what they are. Factors such as management style, procurement strategy and test philosophy are not differentiated. Third, they include all past experience, including errors and overruns. In this respect, these cost models assume no learning curve. As it was in the beginning, is now, and forever shall be! They must therefore be used with great caution. From the systems engineer's point of view, these cost models can be used to assess the relative costs of various design solutions; on an absolute basis, however, they are of little use.

So far we have been able to make a tentative estimate of the cost of the flight system. To this must be added the cost of new facilities, including launch, test beds, flight operations, networks and data reduction, among others, and finally the cost of operations. It is at this point that the program manager faces

the first dilemma: What should be included in the program cost? That sounds like a simple question, but it is complicated by the fact that not all costs are under the control of the program manager, nor is he or she responsible for justifying all of the associated appropriations.

For example, launch costs are provided by the Office of Space Flight, network costs are provided by the Office of Operations, and civil service costs are provided by the research and program management fund managed by the Office of the Comptroller. New buildings are provided under the construction of facilities budget. In addition, most new program managers are surprised to find that a tax based on the number of civil servants working on the program varies from Center to Center, and neither the number of people nor the level of tax is under the control of the program manager. Taxation without representation! Despite this dilemma, the systems engineer should include all of these factors in the cost estimate because the chosen design will affect all of them; overall program costs are as important to the Agency as direct program costs.

Program costs tend to be presented as only those costs that are under the control of the program manager. No matter how much this limitation is stated in presentations, it is assumed that it is the total program cost (especially when it is a popular program) that has the support of the Executive branch, the Congress and other constituencies. It is no wonder that the average program increases in cost by a factor of about three from the time of approval to completion and that most program managers during this period are accused of everything from naiveté to self-deception to outright lies. There is the added ethical question that if all costs were actually presented, the program would not be approved!

Defining the Program

This phase of the program, usually known as Phase B, will take from one to two years. The purpose is to take the various concepts considered in Phase A and select a single valid solution. By the time Phase B is over, a clear set of requirements should be available with a complete set of functional specifications and a cost estimate based on preliminary design concepts rather than on cost models. These are primarily produced by the systems engineering organization and include at least one preliminary design and selected technologies with well-understood risks associated with those technologies.

Don Hearth, former director of the NASA Langley Research Center, performed a study on how much this phase has cost for various past programs as compared to the success of the program in later phases. Success was measured as the ability to maintain performance, schedule and cost as determined at the end of Phase B. He concluded that the most successful programs spent between five and ten percent of the total program cost in Phase B. The scope was limited to unmanned programs, but the rationale can reasonably be extended to manned programs.

Apart from establishing a credible functional system specification, it is essential to determine the management structure, the procurement strategy and a baseline cost for the life of the program, including the cost of operations. Once again, the primary method for cost estimating is the cost model, but there should be sufficient detail available to check the model with bottom-up costs based on feasible design solutions. The systems engineer is responsible for comparing these two cost estimating techniques. It is unwise to proceed to the next phases unless some bottom-up cost estimating has been performed.

Perhaps the most important product of this phase is a complete work breakdown struc-

ture. Again, this is largely the responsibility of the systems engineering organization. The axiom to be followed is, "You cannot control what you have not defined."

Work Breakdown Structure

Too often a program will be approved without a well-established work breakdown structure (WBS) describing the whole program, which inevitably results in large cost overruns. The WBS is the basis for the procurement strategy and often for the management structure. Without it, program changes will take place after the contractors are in place and have to be paid. Overlaps between contracts, as well as missing elements and contract changes, are always expensive. The following simple rules have to be followed:

1. Each element of the WBS should contain a deliverable that can be defined.
2. The sum of the WBS elements must be the total program. (Note that a given program manager may not have the responsibility for all elements, but they should each be defined and allocated.)
3. Each deliverable should be accompanied by a cost and a schedule. The cost should include a reserve based on the estimated risk associated with that element, and the cost should be allocated to that element.

As simple as these rules sound and as much as NASA requires contractors to adhere to them, the internal track record is dismal. We can go a long way toward containing costs if discipline is established early and maintained.

One last word of caution. A WBS element should never be established on the basis of function or organization. These elements are not end items. Other mechanisms exist for identifying these elements, which in general

could be defined as program overhead and not entirely the responsibility of the program manager. They should be recognized for what they are and identified, but they should not be included in the WBS.

Managing the Program

We have now reached the time in the program when promises have been made, deals have been struck, and the program has been approved. All that remains is to deliver. A custom within NASA stipulates that new managers are instilled with the belief that the skills required to sell a program and to define it are different than those required to run it. Certainly some changes can be expected, but I believe that such changes are better if they occur sometime after a phase has been entered and the basic management structures have been established. What the program needs at this time is ownership of the concept, and changes in management will usually result in program changes that inevitably will lead to increased costs. This is particularly true of the systems engineering group that has carefully balanced the requirements against the design and is familiar with the "why" of a decision as well as the "what." So far the total expenditure has been relatively low, but once the contractors are onboard and the manpower begins to build up, costs can escalate at an alarming rate. In a very short time, increases or decreases in performance, extensions or reductions in schedule, and decreases in annual funding will all increase cost.

Design to Cost. There is much talk about design to cost but very little action, and for this there are a number of reasons. Earlier, I mentioned that within NASA there is a tendency to order the three variables by performance first, schedule second, and only then worry about cost. So by tradition, cost tends to be put on the back burner. One of the reasons for this is that during the Apollo program, the cost function was transferred to the budget and program control groups. In a

program where the technical problems were so difficult and the budgets were ample, this was understandable, but this is no longer the case. This situation resulted in a shift away from making the design engineer accountable for cost as well as performance and schedule.

The second problem occurs when the cost is not allocated at the WBS element level, where it can readily be traded against performance and schedule and easily traced. I believe that cost must be allocated to the lowest possible level (a little scary for the program manager), but unless this is done, it will be impossible to hold the designer accountable and unlikely that overall costs will be held in check.

The third problem is that in an organization that prides itself on technical excellence, it is very difficult not to make things a little better; consequently, there are always plenty of ideas around. The credo of the systems engineer should therefore be: "The better is the enemy of the good."

Design to Life Cycle Cost. Over the past decade, the operational costs of NASA programs have steadily risen as a percentage of total program costs, largely due to the fact that programs have a longer life in the operational phase. Whereas 20 years ago operational costs amounted to no more than 20 percent of costs, they are now approaching half of the NASA budget. It is time to place design to life cycle cost on an equal footing with design to cost. The dilemma is that a design that allows low-cost operations will usually demand higher development costs and in turn, this means larger front-end program costs. It is essential that the systems engineer make these assessments. The simplest thing for a program manager to do is walk away from this dilemma and let the operations people worry about it later. As this is becoming an overall problem for the Agency, the ability to make new starts will de-

pend on the ability to ensure that a sufficient percentage of the budget is available for operations.

Unfortunately, it is difficult to get enough operations people to participate early in the program, but I believe it is essential. Some kind of veto power should be established when it comes to making design decisions; too many program managers do not feel responsible for operations costs and perhaps, what is worse, are not held accountable for it. Let there be no doubt that operational costs are unacceptably high. An operational concept must therefore be developed early enough in the program to have an effect on the design process.

Change Control. Once a program is underway, the program manager's responsibility is controlling change, which is inevitable. Earlier I said that you cannot control what you have not defined. It is equally true that you cannot control changing something that is not defined. First know what it is! A complete WBS with allocated schedule and cost is, once again, the key. Change requests must not be limited to solving a technical problem. They must be accompanied by cost and schedule impacts and, just as important, life cycle cost impacts.

In addition, there is always a rippling cost impact caused by change. Other WBS elements may be affected, including items in different contracts or in totally different NASA codes, or line items. For these reasons, change must be assessed at the systems engineering level as well as at the WBS level. Perhaps the overriding rule is that changes should be difficult to approve but easy to implement once the decision is made.

Managing Cost Reserves. A qualified cost estimator would not let a program get started without making provision for cost overruns or reserve. The many uncertainties in a development program make it essential. An

analysis of past programs allows a fairly accurate estimate to be made of what is a reasonable total amount as a percentage of total costs, assuming that the programs are similar. Determining how and when the allowance should be allocated is much more difficult. One school of thought says that reserves should be held at the highest level in the program and applied only to correct unforeseen occurrences. The problem is that this tends to bail out poor performers.

I believe that the reserve should be determined based on the perceived risk of the element when the WBS is formulated. The manager of the element should then be held responsible for the stewardship of the reserve. In order for this to work, some sort of reward system must be established for the manager who does not spend the reserve. In any case, it would be prudent to maintain some reserve at the central level for those things that cannot be anticipated. Just to keep the system honest, a very simple tracking program can be established to follow the expenditure of the reserves at the WBS element level after the fact. I would like to see an indepth study done on this subject.

Traps and Pitfalls

So far we have talked about where cost fits into the program management and systems engineering processes. There are a few areas that may catch the program manager unprepared and a few ideas that may be used to make life a little easier in the future. It may not be possible to implement all of them, but it is worth a try.

Buying In. If you are involved in the selling of the program, the easiest trap to fall into is underpricing the program. Despite stories to the contrary, I do not believe that this is a matter of deliberate low bidding. Although I once heard a distinguished gentleman say that we do business the old fashioned way, we do underbid and make up on change requests. The fact is that every program man-

ager I have ever met was convinced that he or she could do it for less than the past record would suggest. Unfortunately, this usually involves changing the way we do business. I believe that there are less expensive ways, but you should tackle this one at your own risk and only if you have the support of the very top of the organization. The systems engineer must be the conscience of the program manager during this period.

Design to Budget. Let us assume that we have completed a perfect Phase B and that everything is in place, including the rate of expenditure by year. It is a virtually certain that two things will happen. First, with eloquent rationales and spreadsheets by the ton, the various element managers will find a need to increase their funding allocation. One favorite argument will be that the sellers of the program, who are no longer in charge, will be blamed for not understanding the problem. In addition, Congress may add a requirement or two.

Second, the budget will be cut in the Agency, at the Office of Management and Budget, and finally in Congress. At this point, the intricate patterns of dependency between performance, cost and schedule begin to unravel. In the first year, this is not devastating because you can always delay bringing the prime contractors on board. But by the time they arrive, the trap has been set for the most insidious form of management, design to budget. Unfortunately, a fact of life is that very few research and development programs have multi-year funding, and annual budgets will be less than planned. The net effect is that program costs will escalate, and enormous pressures will attempt to bring down the annual funding.

The first remedy is to stretch the schedule, and the second is to reduce the scope of the program. You will no doubt find yourselves in this position, and you will receive a great deal of advice from the nonparticipants, but

you should beware of "descoping." A cursory examination of the cost models will show that in the manned programs, only 20 cents of every dollar go to hardware. (In the unmanned programs, the number is closer to 40 cents.) Once the management structure is in place and the contracts have been awarded, virtually all of the other costs are fixed or very difficult to reduce. Take out all the content and the program cost will still be 80 percent of the estimate! The lesson is that if you are forced to remove content, you should be sure to take out every cent that is associated with that content: prime wraps, nonprime wraps, test beds, personnel, and, if necessary, the kitchen sink. It will be difficult to find, but it will be worth the effort.

If this were a mystery novel, it might well be called "The Case of the Missing 80 Percent." Where does it all go, and why is it only 60 percent for unmanned programs? Much of this is valid and accounts for systems engineering and integration at all levels of the program, including test and evaluation, operations, and many other things. But it also accounts for duplication of test facilities, overlaps between assignments, management style, inefficiencies and a host of hidden costs associated with maintaining the institutions that are often invisible to the program manager. The systems engineer is responsible for ferreting out the good from the bad. It is a simple fact that the first one percent reduction in these wraps (80 percent to 79 percent) increases the amount of hardware by five percent (20 percent to 21 percent)! A 20 percent improvement in the wraps (80 percent to 60 percent) results in a doubling of the hardware (20 percent to 40 percent) or cutting the program costs in half for the same amount of hardware! "Thar's gold in them thar hills."

The UPN System. The NASA budget is prepared and submitted using a system of breakdowns known as the unique project number (UPN) system. All parts of the

Agency are required to report their annual needs on the basis of this system, including the program offices. From a program point of view, a fatal flaw in this process is the numbering system, which generally describes functions rather than end items and is therefore not in consonance with the principles of a WBS system.

It is essential that the program manager be able to trace the equivalence of the UPN number and its corresponding WBS element. This will require a joint effort between systems engineering and the program control people. Without this traceability matrix, the program manager will not know what is being asked for or where the money is going. Too often the UPN number is perceived as directly equivalent to the WBS element, but this is very seldom the case unless the WBS is not end-item oriented. (The latter happens more often than it should.) One way to avoid this situation is to make the annual budget call for the program using the WBS system and then translate it to the UPN system for the purpose of aggregating the total NASA budget. I have never seen this happen.

The Cost of Operations. I mentioned earlier that the costs of operations are now about 50 percent of the NASA budget. This is partly due to the increase in the operational life of a program and to the fact that we have not learned to design systems for operability. It has not been necessary in the past. It is also true that the productivity of the operations infrastructure has not been high on the program manager's list. If we are to reduce total program costs, which are vital to the Agency and to the program, it is time to strike a new level of cooperation between these two normally separate parts. The program and the systems engineer must assume a large part of the responsibility.

The Institution and the Program

Although not directly related to the systems engineering process, a number of things bear

directly on the program and have a major effect on the ability to perform the various program functions. These generally concern the relationship between the program and the institution. NASA was originally established using the resources of the National Advisory Committee for Aeronautics, known as NACA, an aeronautical research organization that was seldom involved in large development programs. The budget was relatively small, and there were few contractors. In fact, all contracts were signed at the Washington office, the NACA equivalent of Headquarters.

It quickly became apparent that, in addition to the research centers, a development center was needed. Goddard Space Flight Center (GSFC) was established to perform this function. This was rapidly followed by the Lyndon B. Johnson Space Center (JSC) in Houston, the George C. Marshall Space Flight Center (MSFC) in Huntsville, and the Jet Propulsion Laboratory (JPL) in Pasadena. Almost immediately, GSFC and JPL became responsible for multiple unmanned programs, which were largely contained within a single Center, and JSC and MSFC became responsible for multi-center manned programs. In both cases, program offices were established and the Centers provided the resources, both personnel and facilities, to support the program.

With the exception of JPL, which is a Federally funded research and development center and operates outside the civil service system, all NASA personnel and basic facilities are funded separately from the programs in line items known as Research and Program Management (RPM) and Construction of Facilities (CoF). Program-specific facilities are funded by the program and these facilities are most often operated by support contractors, also funded by the program. This system was established so that the programs would be managed by government personnel who would rotate from program to program

and carry their experience with them. This worked very well until the late 1960s when the budget began to fall rapidly, and there was a significant reduction in NASA personnel.

By the early seventies, both the budget and the number of personnel had been cut in half, but the number of Centers remained essentially the same. The cost of maintaining the institution could no longer be sustained by the RPM and CoF line items. The solution was to tax the programs based on the number of personnel that were applied to the program. Unfortunately, the program manager does not decide how many people should work on the program, which, by tradition, is the responsibility of the Center director. Neither does the program manager participate in determining the level of the tax. These decisions, again by tradition, are made by the comptroller.

Maintaining the Institution

Unless the basic system of funding personnel is changed, the programs will most certainly be responsible for funding some of the institutional costs that are not related to the program; the RPM budget will never be allowed to grow to compensate for this. The question is rather how large the institution needs to be to support the program and how that decision is made. I mentioned earlier that the WBS should represent the totality of the program and should always describe deliverables; this problem runs counter to that principle. I believe that the solution lies in accepting this cost for what it is, negotiating the level of tax with the program manager for the duration of the program, and taking it off the top each year. It may not be controllable in the normal sense, but at least it is a known number.

Personally, I believe that the Agency would be better served if the development centers were managed using an industrial funding system similar to JPL and many other gov-

ernment facilities, including the Navy labs. But until that happens, it will be necessary to find some balance between the institutional and program needs.

Management Stability

Every program will change management during its life cycle. The common practice in NASA has been to make these changes deliberately between phases. It is not uncommon to see as many as four different managers during a program, including a specialist in closing off completed programs. The positive side to this is that it is possible to match the needs of each phase of a program to the special capabilities within the Agency. The negative side is that each manager has a different style, each program has different management needs, and often these do not match when the changeover occurs between phases. One way is not always right and another always wrong, but each is different, and changes even in management style can, and usually do, increase the cost of the program. The secret then is to stick with a team as long as possible, particularly the systems engineering team, something that is easy to say and difficult to do in these times of declining internal expertise and increasing retirements.

The Tyranny of Experience

Too often, you will find resistance to change in the way things are done. "We have always been successful (measured by performance) doing it this way, and it's very dangerous to change winning ways." "If it ain't broke, don't fix it." "You get no credit for an on-time failure." All true and at the same time, destructive to valid new ways of doing business, especially when it comes to introducing more efficient or less expensive ways. When the space program started, we had no experience and what followed was the most innovative and exciting period in the history of high technology programs. But now we have all that experience, and it has become a burden. By all means, you should keep the wise

heads around (they may still save you), but take advantage of the explosion in new technologies and capabilities, which allows for things that we could only dream of 30 years ago. You should be careful before you introduce a change, but you should not dismiss it out of hand.

Does It Matter?

We have been in the civilian space business for almost 40 years, and time after time we have shown that we can rise to any challenge and lead the competition, provided we have the resources. Time and time again the Federal Government has provided the resources. We have been the envy of the world. We have written the book on the subject, both from a technical and a management sense.

Until now, it was enough to know that we were the best. There was no established competition, most of the money was spent internally, and cost efficiency was second to performance. Some have characterized it as a Works Projects Administration (WPA) for the technologists! The problem is that in this era of budget deficits and trade deficits, there is not enough discretionary money to go around. Even without international competition, it would be imperative to get more out of our research dollars. The trouble is that we have learned profligate ways, as neither the government nor the contractors give rewards for cost efficiency. While we were

basking in this glory, the rest of the world has been catching up; they have read the book. The competition, supported by their governments, is getting good and fierce.

But there is a difference; the competition believes that the space business is here to stay. I said space business, but I meant commerce, and in commerce cost efficiency is paramount. Do we still want to stay at the top, or are we ready to leave it to the rest of the world? Are we prepared to do what is necessary to stay in the game? After all, it's only a space program. Does it matter? You bet!

Can Anything Be Done?

In this paper, I have attempted to show where cost fits into the space program's engineering and management business. A combination of things have placed cost at the bottom of the priority ladder except in matters of the inexorable annual budget. There are many ways to improve cost efficiency, some of which are available to the program manager. In the long run, it will take a concerted effort by all of us to make a difference. The Executive branch and Congress, together with industry and academia, must work as before, when we perceived that we were second. In the meantime, I hope that I have been able to give the budding systems engineer and program manager a few tips to do something about the problem of cost considerations. We can only do something about it if we want to!

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ESTIMATING THE COSTS OF HUMAN SPACE EXPLORATION

by Humboldt C. Mandell, Jr., Ph.D.

The strategic plan for NASA's new exploration initiative begins:

On July 20, 1989, the President of the United States committed the nation to a major initiative to explore space. The goal of this initiative is human exploration of the Moon and Mars as soon as possible within the constraints of national resources.

From several years of studying alternative strategies and debating the relative merits of national investments in space exploration has emerged a consensus; i.e., that expanding human presence and activity beyond Earth orbit is an appropriate and inevitable long term focus for the nation's space program.¹

The plan states three strategic themes: incremental, logical evolutionary development; economic viability; and excellence in management. All of these intricately involve the cost estimation process, and, as will be shown, will be completely dependent upon the engineering cost estimator for success.

The purpose here is to articulate the issues associated with beginning this major new government initiative, to show how NASA intends to resolve them, and finally to demonstrate the vital importance of a leadership role by the cost estimation community.

The Demand for a New Management Paradigm

The exploration program objective, as stated in the *NASA Strategic Plan*, emphasizes early accomplishments, but also recognizes that the environment today is substantially different, and that whatever is done must be done within the limits of realistic budgets.

This presents a double challenge to NASA, where the length of a human mission spacecraft development program has approached a decade. For a new era of space exploration to begin at all, it is believed, early milestones must be set which are challenging and attractive to those who must provide program resources (the National Space Council, OMB, Congress), oversight bodies which have sent strong signals that multibillion dollar exploration programs requiring decades to reach fruition are not in NASA's future. NASA must therefore provide early, visible, worthwhile milestones in exploring space.

At the same time, costs must be reduced. Generally, compressing a given task into a much shorter period of time will greatly increase the annual funding required. NASA must find ways to compress and at the same time *lower* annual funding requirements. Already, the experienced engineer/estimator will begin to have concerns. Accomplishing these challenges one at a time is difficult enough, but to accomplish both at once is beyond the paradigm of conventional aerospace program management, on which almost all of our estimation methods are based.

Another example of the problems with the conventional aerospace management paradigm is illustrated by the case of the Space Station program. That program struggled to lower annual budgetary requirements by reducing the mission content of the program; but the more the program is modified, the more changes are incurred, the *higher* the total program cost, and the more pressure on annual budgets. Reducing content can achieve the most significant cost savings before the program is started. Once underway, content reductions often exacerbate an already bad cost situation.

The situation is made even worse by the absence of good tools. Every cost model employed by the aerospace industry today (with perhaps one or two exceptions) merely predicts the future based on the behavior of the past. If, then, extrapolation of past behavior will not produce the desired result, how can cost models based on that behavior serve us at all? NASA has learned that they cannot. In fact, they can become the tools of those who oppose new programs, to prove to the Congress and the Administration that undertaking of the grand new adventure is folly. Of course, the point would not have been proven at all, but the perception of proof is at least as powerful as proof itself. One can look for situations of this nature to arise within the next few years. The cost estimator, then, can become the enemy of progress. Or, as will be demonstrated, he or she can lead the way to change.

Struggle as we will within this old paradigm, we will not be able to resolve the dual challenges of lowering annual costs substantially while significantly reducing program length. Impossible. So, what can be done? Should NASA simply go the President and admit defeat? To do that would probably doom what remains of the human adventure in space, and not only jeopardize future programs, but raise the question of the continuation of current programs as well.

When a problem cannot be resolved within one paradigm, it is obviously necessary to change to a new one. But before that new paradigm is defined, a direction must be established, and a model created for the new. To change course without a new destination would be equally disastrous. The research done by NASA to identify that new model follows.

A Summary of the Cost Challenges Facing Exploration

Much of the planning of any new venture involves matching demands for resources with

the predicted supply. Within the old paradigm, the supply of resources has often been predicted only by estimating the demand. In former times, this process has worked because the aerospace and defense industries have generally received ample support from the nation to create this norm.

However, the norm is today being threatened. As each new human space venture since the initial Apollo lunar landing has been launched, the availability of resources has become increasingly scarce. The Space Shuttle, a program designed to lower the cost of placing humans and cargo into space, defeated its own *raison d'être* when it was forced, for reasons of annual budget limits, to eliminate its completely reusable booster, and to limit the availability of on-board autonomy which would have reduced the expense of ground control and checkout.

Similarly, Space Station Freedom was beset from the outset with mission compromises caused by annual budgetary limits, and became a much less capable facility than was originally conceived by NASA. Each year the program suffered further and further content reductions in an attempt to meet annual cost constraints.

Today's situation has found the nation even less able to pay for large, new manned space programs than ever before in our spacefaring history. But it has taken some time for this realization to influence the program planning paradigm. For example, as recently as 1991, the Advisory Committee on the Future of the U.S. Space Program was making recommendations to the NASA Administrator which, while recognizing that there were budgetary constraints, were predicated on the availability of greatly increased NASA budgets (see Figure 1).

As NASA began its studies of human exploration missions under the old management paradigm, the cost models employed pro-

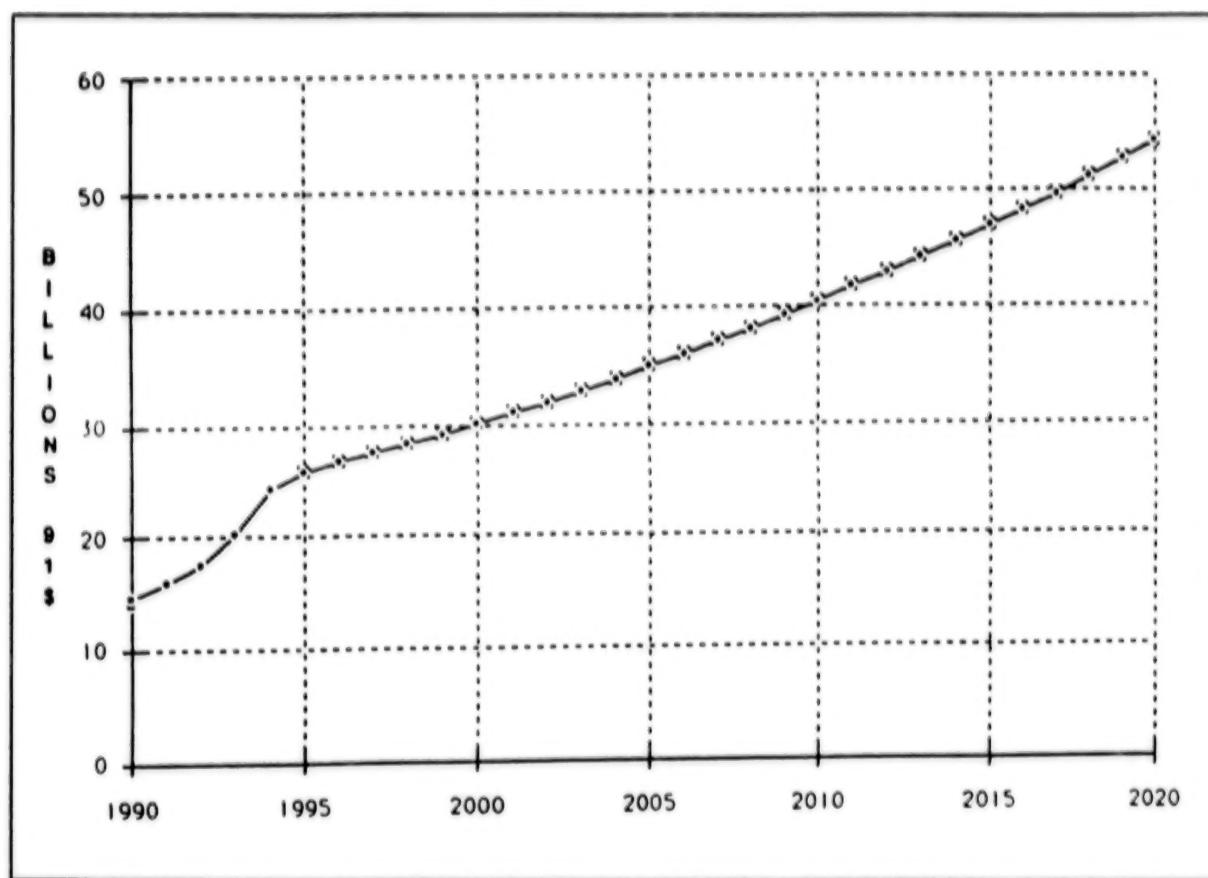


Figure 1. Budget Assumption of the Advisory Committee on the Future of the U.S. Space Program

duced estimates such as those shown by the middle curve of Figure 2. Overlaid with the budget projections of the Advisory Committee on the Future of the U.S Space Program (top curve, Figure 2), there seemed to be no reason to doubt that exploration had a bright future.

However, when better budgetary estimates were made with econometric models and with full understanding of the true likelihood of NASA budget growth (lower curve of Figure 2), the dilemma became apparent to some for the first time.

Four Things Which Must Be Done

To resolve the dilemma of budget growth, NASA must do four things. First, full attention must be paid to the mission statement of the opening paragraph: "to the Moon and to Mars as soon as possible, within the constraints of national resources." With a focus

on the purpose of human exploration, the need for much of the content of previous planning exercises can be questioned, and missions constructed which contain only mission-related items.

Second, existing NASA and other governmental resources must be found and leveraged. For example, much of the money currently being spent by NASA on science and technology is fully applicable to the purposes of human exploration; however, some mission focus must also occur in these areas. The use of other federal resources can include the use of national laboratories and DoD assets, and these are being investigated.

Third, NASA must implement a new management paradigm which does things faster, smaller, and less expensively, using the enormous cost leverage which results from cultural change.

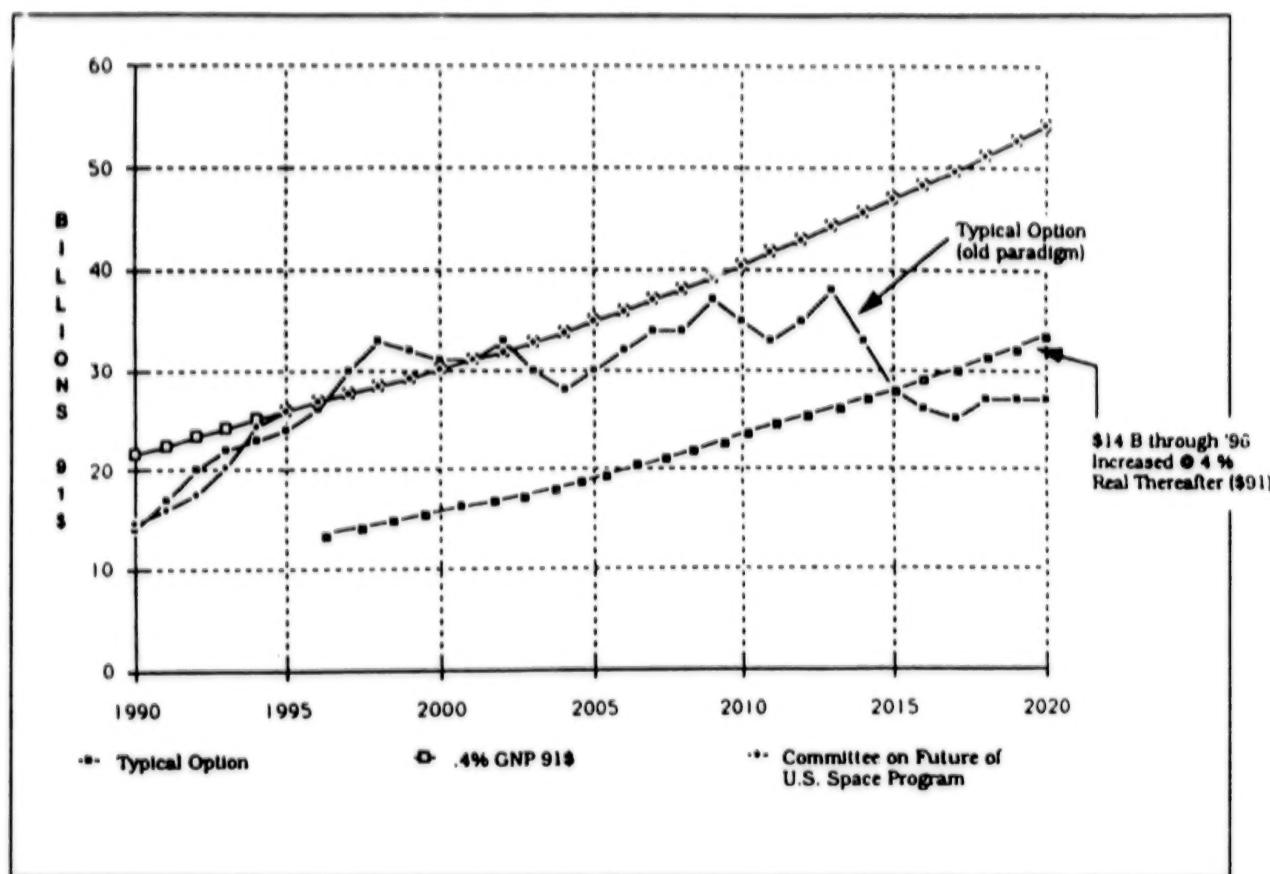


Figure 2. Comparison of Budget Availability Models

And finally, some new resources must undoubtedly be found for NASA. These will be much more likely to be forthcoming if the Agency once again gains the full confidence of the Congress and other oversight groups by demonstrating competence and efficiencies associated with the change to the new management paradigm.

Benchmarks for the New Paradigm

NASA is conducting research to identify benchmarks, guidelines, and processes for the low cost, short schedule paradigm. Extensive interviews have been conducted and analyses performed to identify high technology programs which have been done under different management norms, and which have resulted in high performance, low cost, quickly developed products.

Results of the interviews, summarized in Figure 3, indicate a wide consensus on the

part of those successful managers interviewed, that NASA should confine itself more to the development of good, performance-based requirements, and establish a more arms-length relationship with the private sector to allow the power of the competitive marketplace to produce excellent products.

Historically, the highly interactive relationships between NASA and its contractors have produced excellent products, but program change rates have been in the thousands per year, and high costs and long development schedules are typical. Contractor awards should be based on the performance of products as demonstrated in mission performance. Taken altogether, the findings of this research, as summarized, provide very useful benchmarks for designing future program management processes. But do these findings describe a feasible set of conditions?

Another part of the NASA research has dealt with the identification of programs which have been accomplished more under the described new set of conditions than under the existing aerospace paradigm. Programs like the XR-71, the F-117, and the YF-16 (Lockheed, Lockheed, and General Dynamics, respectively) have demonstrated that high technology programs can be done very quickly (all of these programs produced flying aircraft in approximately two years) and at costs significantly below those which would have resulted from the old paradigm.

However, much more work is needed by the industry to plan and execute an orderly transition from one culture, one paradigm, to the new paradigm for NASA space exploration. The cost estimator can play a key role in the process.

Cost and Culture: The New Calculus of Cost Analysis

Cost estimation methods employed by the aerospace industry for program planning are usually parametric in nature, although some detailed estimating is used for special purposes which do not readily lend themselves to performance or size-based parametrics.

In most parametric estimation, for reasons that parametric estimators seek the best possible analogies from their historical databases, the implicit assumption is that a new program will be a product of basically the same cultural and management conditions (the same paradigm) as programs of the recent past. However, when this assumption is made for exploration programs, the resulting estimates exceed realistic budgetary expectations.

The ingredients of successful low-cost, high technology programs are well known and universally recommended by successful program managers interviewed

- Use government only to define requirements
- Keep requirements fixed: once requirements are stated, only relax them; never add new ones
- Place product responsibility in a competitive private sector
- Specify end results (performance) of products, not how to achieve the results
- Minimize government involvement (small program offices)
- Insure that all technologies are proven prior to the end of competition
- Utilize the private sector reporting system: reduce or eliminate specific government reports
- Don't start a program until cost estimates and budget availability match
- Minimize or eliminate government imposed changes
- Reduce development time: any program development can be accomplished in 3 to 4 years once uncertainties are resolved
- Force people off of development programs when development is complete
- Incentivize the contractor to keep costs low (as opposed to CPAF, CPFF of NASA)
- Use geographic proximity of contractor organizations when possible
- Use the major prime contractor as the integrating contractor

Figure 3. Benchmarking Lessons Learned from Interviewing Successful Program Managers

Therefore, one must conclude that, if major exploration programs are to be performed, significant cultural change to a new paradigm is an absolute necessity. However, except for the G.E. PRICE series of models, the aerospace industry cost estimator is not equipped to deal quantitatively with cultural change as an explicit variable using the existing tools and databases. It has, therefore, been necessary to construct a new type of cost model, which, instead of predicting costs from "technical" and performance parameters, will predict the cultural levels required to produce a given cost outcome.

Working with the then-RCA PRICE Systems organization, NASA performed a study to determine the effects of various culturally imposed standards on costs. The study results² demonstrated conclusively that, while there is correlation between cost and such things as government-imposed parts traceability re-

quirements, major differences still exist in program costs which can only be explained by the organizational "manner of doing business," or culture of the developing agent.

These results have recently been repeated by Kelley Cyr of NASA's Johnson Space Center and employed in the development of a new series of cost models. Figure 4, based on a statistical analysis of several hundred points of data, portrays the quantified relationship between cost and development culture.

In the current environment, this type of cost equation provides the needed utility to relate costs to program management and manufacturing culture. Particularly in government aerospace product acquisitions, the highest levels of product performance have been for over a generation the object of most development efforts in the industry. This has created a culture where program cost, while highly

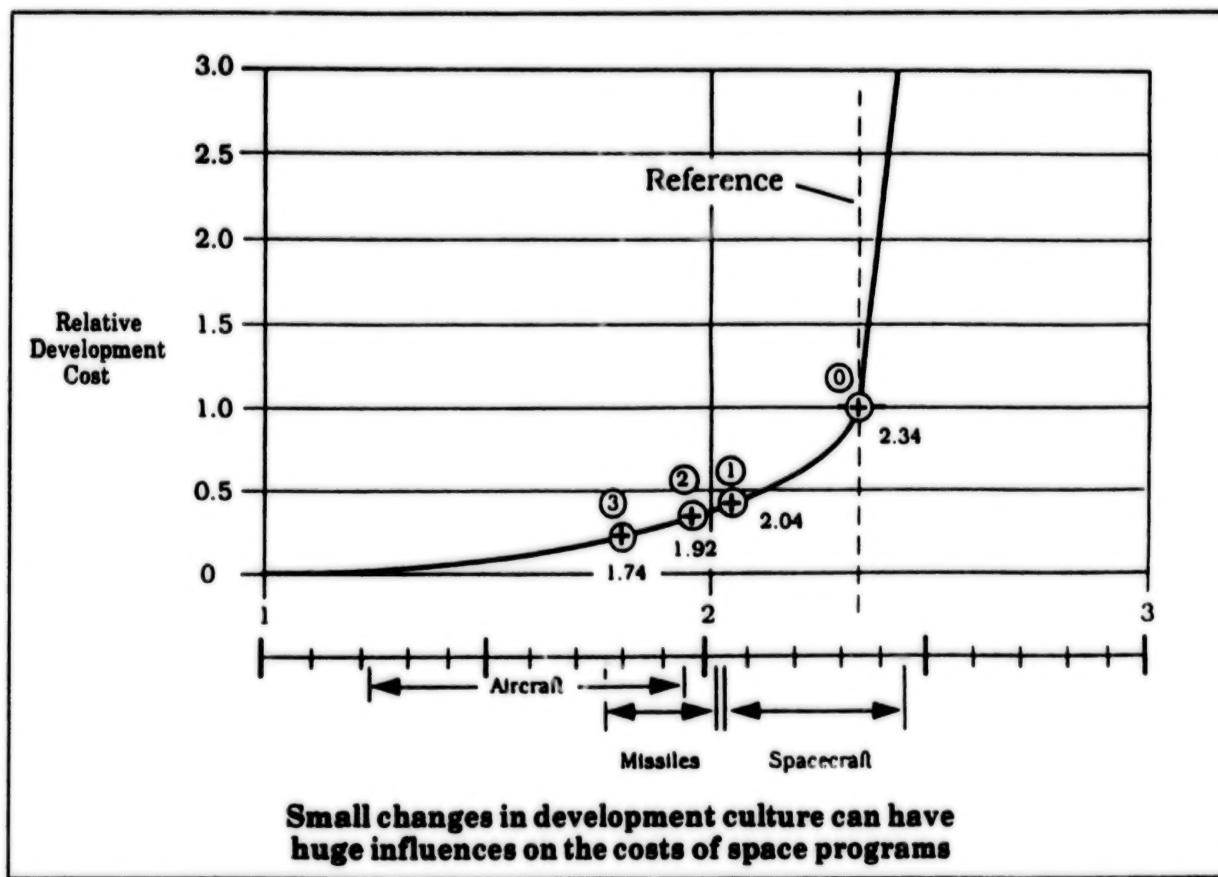


Figure 4. Effect of Development Organization Type on Program Development and Production Cost

important, has not generally been treated as a critical design parameter.

In this climate, it is not surprising that many design engineers and program planners are generally not well equipped to deal with cost as an explicit parameter. Who, then, is available to provide the leadership which will be so vital to the conversion of our industry to lower cost, shorter schedule norms?

Who is closest to the necessary data? Who has the best understanding of the dynamics of engineering processes as they are influenced by costs and schedules? Who (often) has training in both engineering and business practices? Who is most often the one who bears a major responsibility for any major cost reduction activity? It is proposed here that there is no one better equipped than the company cost estimator. The case can be made that the cost estimator is best able to provide answers to all of these questions.

In the case of the exploration initiative, the activities of the cost estimation team will have the most significant influence of any on the future success of the venture. That team must not only develop compelling cost estimates, but they must also lead the way in providing the rationale, the supporting arguments, to provide cogent reasons why NASA can truly accomplish what it proposes (such as returning humans to the Moon by 1999) within the available budgets. It is also the cost estimation team who must provide the information for the design teams to utilize in developing requirements for low-cost, early

missions. They may be the only team who can complete the bridge to the new paradigm. If they fail at this, the entire venture will probably fail to be accepted by the Congress and the Administration.

The aerospace industry cost estimating community holds the future of the United States Space program in its hands. While this community is not unto itself sufficient to develop the new initiative, it is vitally necessary.

Conversely, the cost estimating community is totally sufficient to prematurely end the life of American space exploration, at least for this generation. It is far easier to develop strong arguments for why the nation cannot afford to send humans to the Moon and to Mars than it is to prove that it cannot afford not to do it. It is far more comfortable to fall back on that which has served us well in the past and hold to the old culture, to stay with the old paradigm. It is far easier to use our existing, culturally-bound costing methods than it is to seek methods which can point the way to changes that may brighten the future of our entire profession, if not our industry.

The job of cost estimators has never been easy. The results of their work have often determined whether or not their company wins or loses a major competition. But today, it is the cost estimators who wield the enormous power of life or death over the future of the United States space exploration program. It is earnestly hoped that this awesome responsibility will not be taken lightly.

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THE ADVANTAGES OF COST PLUS AWARD FEE CONTRACTS

by William C. Keathley

Personal experiences in the management of projects and shared experiences with colleagues have convinced me that a Cost Plus Award Fee contract is the best procurement vehicle for the high-tech, one-of-a-kind, development projects that constitute most of NASA's projects. But, like most things, success isn't automatic. It takes work to make it happen, and the successful implementation of award fee contracts is no exception. In fact, the use of this type of contract requires more government and contractor effort than other forms of contracts. But, in my opinion, it's worth every hour spent.

Over the years, I've collected a list of "lessons learned" related to the use of award fee contracts. I'll try to articulate those lessons adequately in the following text. Keep in mind that I'm not speaking from the standpoint of a procurement officer. My observations come from the day-to-day use of these contracts in various positions I've held—project manager, director of flight projects (project manager's supervisor), and fee determination official.

An award fee contract is described as an arrangement whereby the government periodically awards a fee consistent with the cost, schedule and technical performance that is achieved by a contractor during a preset period with preset award fee pools.

Rationale

Let me explain why I like award fee contracting. First, it's the only contracting method where both government and contractor goals are closely linked. The government wants cost, schedule and technical performance; the contractor wants profits. The better the total performance, the better the fees (profits) will be. Compare that with a fixed price contract where the total price (cost plus fee) is fixed. If

the cost of a fixed price effort is underestimated, the contractor may sometimes make adjustments that impose risks to the technical performance. This protects the contractor's profits but imposes risk on the government's goal for technical performance. Other ways exist for contractors to protect their fees in a fixed price arrangement (all of them bad for the government), but that subject deserves a separate paper.

Second, an award fee contract has a built-in mechanism to conveniently alter and emphasize program events in order to satisfy current external and internal situations—and the government is involved in these adjustments. Prior to each award fee period, the government and contractor project managers review the plan for the upcoming period, agree on the planned events, and place the appropriate emphasis on each event. Should problems arise (and they always do), the plan and the fee emphasis can be adjusted accordingly. This is considered by most project managers to be the most important feature of award fee contracts.

And while I'm on adjustments, I'd like to mention the use of "rollovers," in which lost fee from prior periods is used to "sweeten the pot" on future events that have become so critical that additional emphasis is warranted. Rollover is a powerful award fee tool to motivate contractors if used properly.

Third, the award fee process demands good communication between the government and contractor participants. And every project manager knows or should know that good communication is a necessary ingredient of every successful project. The meetings required by award fee contracting reinforce the need for clear communication.

Fourth, I have learned that contractor performance on award fee contracts is superior to performance by the same contractors on other types of contracts. The quality of the product is certainly superior. The fee earned by those contractors is better than they could have received on other cost type contracts, and it should be. Remember: better performance, which the government wants, results in higher fees, which the contractor wants. I don't have any data on fixed price contracts because there is no government knowledge of final costs of those types of contracts. But I'll bet award fees are close to the profits customarily realized by contractors, even on fixed price development contracts.

The downside to award fee contracting is the additional contractor and government personnel required to implement award fee contracts. It is certainly true that more people are needed to formally assess contractor performance, conduct performance evaluation board meetings, and report findings to the fee determination official. But I maintain that most of that work should be done under any circumstances, and the improved communication is worth the effort. So I'm not sympathetic to those complaints.

Implementation

All the good features discussed above can go down the drain with faulty implementation. I've found the following nine ground rules to be effective in properly implementing the award fee contracts in which I've been involved. I will readily admit that there should be many ways to skin this cat, but frankly, I've found no effective alternatives to the following rules. I've also seen instances where both the government and the contractor failed to reach their objectives as a direct result of deviations from one or more of the following rules.

First, the government project manager must chair the Performance Evaluation Board

(PEB). After all, the project manager is the key official selected by NASA to be responsible for the project cost, schedule and technical performance. The project manager is in the best position to evaluate the importance of the performance during the project evolution and obviously has the most to gain or lose from that performance or lack thereof. If that's not true, the Agency should find another project manager. On the other hand, it's crucial that the contractor understand that the government project manager is the most influential government individual for all project activities, and looking elsewhere for project-level influence is unproductive.

Second, the PEB should consist of institutional members who are participating in the project: procurement, business (program control in some Centers), engineering, and product assurance (quality control and safety at some Centers). Depending on the end item or service, science and operations should also be added. It's advisable to keep the PEB membership as small as possible, and it's important to select individuals with experience applicable to the end item or service delivered. In other words, make sure they are capable of understanding what the contract monitors are telling them.

Third, the Fee Determination Official (FDO) should be no higher than one level above the project manager and, in fact, should be the project manager's line supervisor. The FDO must have more than a passing knowledge of the project's status. This requires frequent interactions with the project manager, which the supervisor's position provides. Deviations from this rule can result in some awfully dumb fee determinations. I might add that if the project manager reports to the Center director, the deputy Center director should be the FDO. Center directors should not be FDOs and should be reserved to resolve institutional or project issues should they arise.

Fourth, use adjectives that can be understood and that properly describe performance levels. I prefer the academic model where "Satisfactory" is used for barely passing performance (a 60 or 70 percent performance rating, depending on your preferences.) Levels below "Satisfactory" can be identified as "Poor" and "Failing." Levels above "Satisfactory" can be called "Good" and "Excellent." It's confusing to everyone when fee curves are set so that the fee letter indicates a contractor got a "Superior" rating but received only 65 percent of the available fee for that period. Don't laugh; that's actually happened.

Fifth, skew the fee curve (fee earned vs. performance rating) so that most of the available fee falls above "Satisfactory," or whatever you've decided to call passing performance. This clearly shows our desire for high performance and motivates the contractor to exceed a mere passing grade.

Sixth, make the award fee periods sufficiently long to allow time to correct deficiencies after a midterm review by the project managers. I prefer six-month periods. This allows the project managers to assess the performance status three months into the period in order to identify performance problems, and then still provides three months to correct the situation before final evaluation and scoring of that period's performance. Periods of less than four months preclude this important process.

Seventh, offer contractors an opportunity to present self-assessments of their performance to the PEB and the FDO. Some contractors will choose not to do this, but the invitation ought to be given. If the offer is accepted, I believe the PEB should hear the contractor's self-assessment before making the final rating. As an FDO, I definitely preferred hearing the contractor's self-assessment before hearing the PEB's story. I've found that the major advantage of contractor

self-assessments is that they indicate faulty communication between the government and the contractor—which will kill a successful project more quickly than anything I know.

Eighth, rollovers should be allowed in the award fee plan but never promised. They should be left to the discretion of the FDO and result from recommendations by the PEB. They should be used infrequently and always targeted to specific events that have become crucial to the success of the project. Specific "go/no-go" performance criteria must be established for these events and announced in the fee letter for the period preceding the period in which the selected event falls.

Finally, and most importantly, the contractor project manager and the government project manager *must* jointly agree on milestones and criteria, and the emphasis to be placed on each, *before* the beginning of each award fee period. And then *everyone must stick to the agreements*. This won't eliminate disagreements with the amount of fee awarded, but it does eliminate surprises, which are simply unacceptable. Nothing can kill an award fee process quicker and demoralize contractors more than to be "dinged" for something they didn't know.

Fee Determinations

Now let's look at the lessons learned in the awards themselves. The first and most important ground rule is: *don't play games*. If the contractor earned all of the fee, by all means award it. Don't fall into the trap of telling yourself, "If I give 100 percent, the contractor will start expecting it every time." Or: "The contractor earned 100 percent, but I'll give 80 percent to give some room to improve." Or just as bad: "If I give the contractor the 20 percent really earned, I'll get the project manager fired." Awards that are too high or too low are equally bad. Awards that are too high tell the contractor to under perform and get away with it. Awards that are

too low tell the contractor that no matter how hard the work and how much the accomplishment, efforts will be in vain. Both situations are bad and will demoralize the contractor. Stick to the prior agreements and award the fee consistent with the actual performance.

If the performance is deficient and your awards are consistently fair, you'll soon see the performance improve. If the performance is good, and the contractor is convinced that fees will be lost by backsliding, the performance will remain high. In case you didn't notice, the operating word is *fair*. By the way, it's a good idea to keep histograms for the percentage fee earned as the program develops. If the awards have been consistent (fair), you'll see the hills (good times) and valleys (problems) that occur in any development activity.

Award Fee Letter

Now for the important fee letter where you tell the contractor about the determination. Believe me, you can ruin a good award fee process and all the work you've done by issuing an award fee letter that no one understands. It would be impossible to overstate the importance of these letters.

I've found the letters should have four basic parts. The first paragraph is really a boilerplate paragraph that references the contract title and number, identifies the period for which the award is given, states the percentage of the award earned and the specific dollar amount, and gives the performance adjective rating. The second paragraph should identify the instances of commendable performance. Be specific, even if you have to use bulleted items. Be clear. The contractor must understand which ratings were high so as to pass the accolades along to the working troops. The third paragraph should identify deficiencies. Again, it's extremely important to be specific and clear. I call the final fourth paragraph the "message" paragraph. The content of this paragraph can range from

"keep up the good work" to "be advised that continued inferior performance in (a certain area) will have serious effects on future overall fee determinations."

A good contractor general manager will do several things with the fee letter; that is, if it is understood. First, a meeting with the project manager will be held to review the letter. The project manager will be commended for the things done properly (second paragraph), actions will be identified to correct recurrence of the deficiencies (third paragraph), and the message (fourth paragraph) will be discussed and actions (project or institutional) will be identified to respond to the thrust of the message.

Next, the good general manager will send a letter to the FDO stating that the award has been reviewed with the project manager, the recognition of the commendable items is appreciated, the deficiencies and message are understood, and appropriate actions have been assigned. In addition, the general manager will now be in a good position to report the profit status on this contract and articulate the details of the award. All of these good things transpire when the contractor understands the fee letter. Otherwise, there is no follow-up or feedback, the situation cannot be explained to corporate reviewers, and everybody loses.

The understanding of the awarded fee is so important that I added one more step to the process. As an FDO, if a general manager called and verbally complained about certain elements of the award, I would discuss the call with the government project manager and provide verbal feedback to the general manager. If the complaint came in writing, I would reconvene the PEB with instructions to draft a written response to *only the specific concerns* stated in the general manager's letter, not every element of the award. I would then discuss the recommended government response with the PEB. If I agreed with the

PEB position, I would send the written response to the general manager. I have changed a prior award in the contractor's favor after learning that the PEB used erroneous information. In that case, the general manager was correct and the contractor earned the fee increase. After all, that was the *fair* thing to do. The contractor response to that small dollar change was tremendous, and performance improved markedly.

So in summation, I believe that award fee contracting is particularly suited to the one-of-a-kind development projects which constitute most of NASA's efforts. I do not believe fixed price contracts or fixed price plus incentive contracts belong in this environment. Perhaps someone else may wish to argue the advantages of the latter types, but my experience suggests that award fee contracting is the better way to go.

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A COST AND PERFORMANCE SYSTEM (CAPS) IN A FEDERAL AGENCY

by W.F. Huseonia and P.G. Penton

The John C. Stennis Space Center (SSC) in southern Mississippi serves as NASA's primary facility for propulsion testing. This includes testing stages and propulsion systems, for the Saturn V moon rocket during the Apollo lunar landing program, and currently, for the Space Shuttle. In addition, SSC is building new test facilities to advance turbomachinery technology for propulsion systems of future generations of vehicles.

SSC also has capabilities in remote sensing, Earth sciences and applications development. SSC is NASA's lead Center for the commercial development of space remote sensing technology and has substantial work under way in the transfer of technology to the public sector. SSC also provides technical and institutional support services to 18 other Federal and state agencies in residence.

Although our principal mission for NASA is to support the development and acceptance testing of large propulsion systems for the Space Shuttle, National Launch System (NLS) and the Advanced Solid Rocket Motor (ASRM), the remaining missions of the Center foster cooperative research and development activities that serve to broaden our understanding and management of our natural resources. These missions are described in Figure 1.

SSC is organized in a classical government functional project structure. The functions of Legal, Public Affairs, Personnel, Resources, Procurement and Safety are shown in Figure 2. There are two project offices (ASRM and NLS) that carry out their responsibilities in a matrix organization with the line directorates. The three line directorates (Propulsion

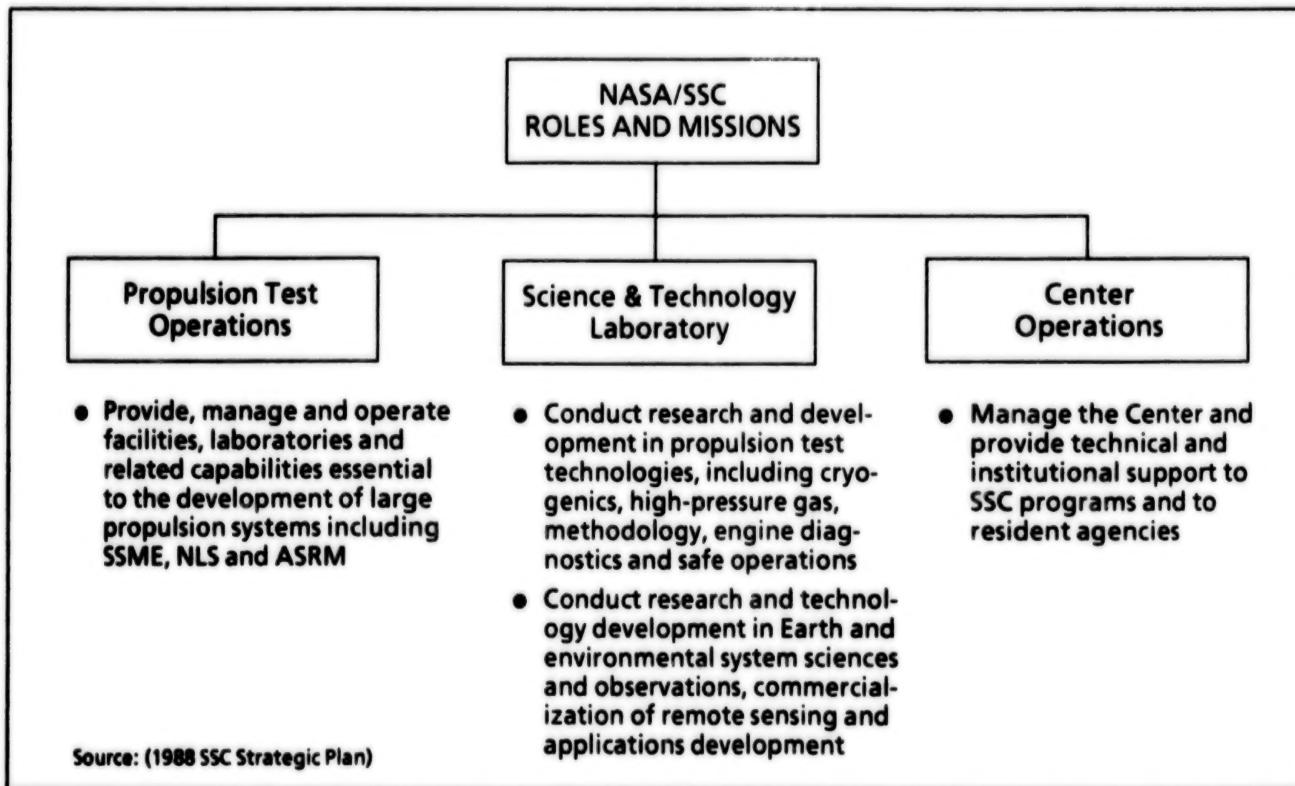


Figure 1. SSC Roles and Mission

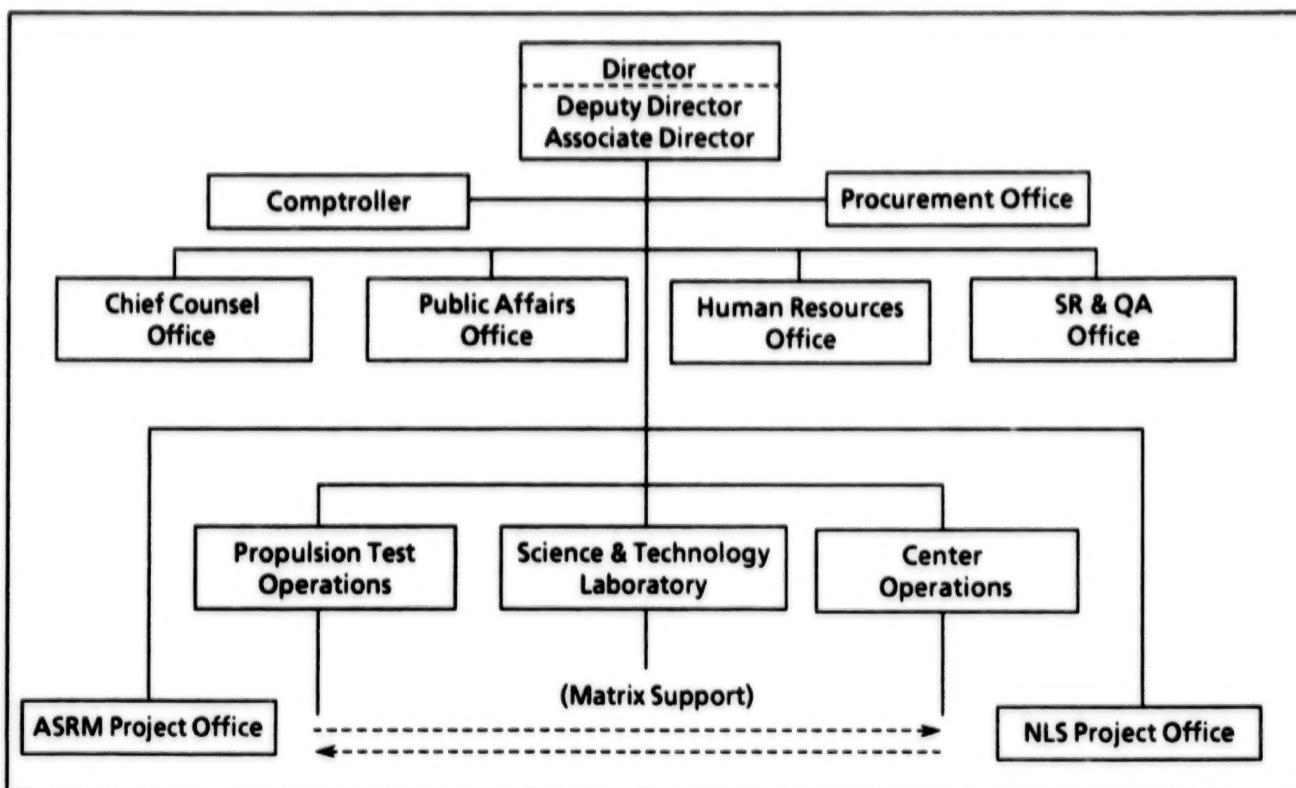


Figure 2. SSC Organization

Test, Science and Technology Laboratory and Center Operations) are functionally compatible with the SSC mission.

This organization structure, a hybrid of functional and matrix, mixed with the fact that the missions of the center are primarily accomplished by support contractors, makes the tracking of cost, schedule and performance a complex and difficult (yet necessary) management function.

Purpose

In the late 1970s, the NASA Administrator established a study to examine NASA project management and to make recommendations on how to improve the Agency's performance. A major conclusion of the study was "poor tracking of contractor accomplishments against approved plans in a timely fashion leads to late identification of problems" (Hearth, 1991).

This paper describes a systematic approach to aligning funding sources with cost plan-

ning and performance scheduling. This system establishes a monthly reporting status structure, correlates resources with schedule and performance, and assesses "what-ifs" and their alternatives for management review (Snead, 1991). The Cost and Performance System (CAPS) provides the foundation for successful project management, functional organization management and oversight of the total organization's performance.

This system will be described in generic terms with results and implications from its specific use directly relating to the Science and Technology Laboratory (STL) at SSC.

Planning Phase

The model depicted in Figure 3 begins with a fund source and its identification within the federal financial system as a Unique Project Number (UPN). The UPNs are assigned according to the NASA Headquarters organization and program structure and tracked at various levels in the organization. For example, NASA may assign a three-digit UPN

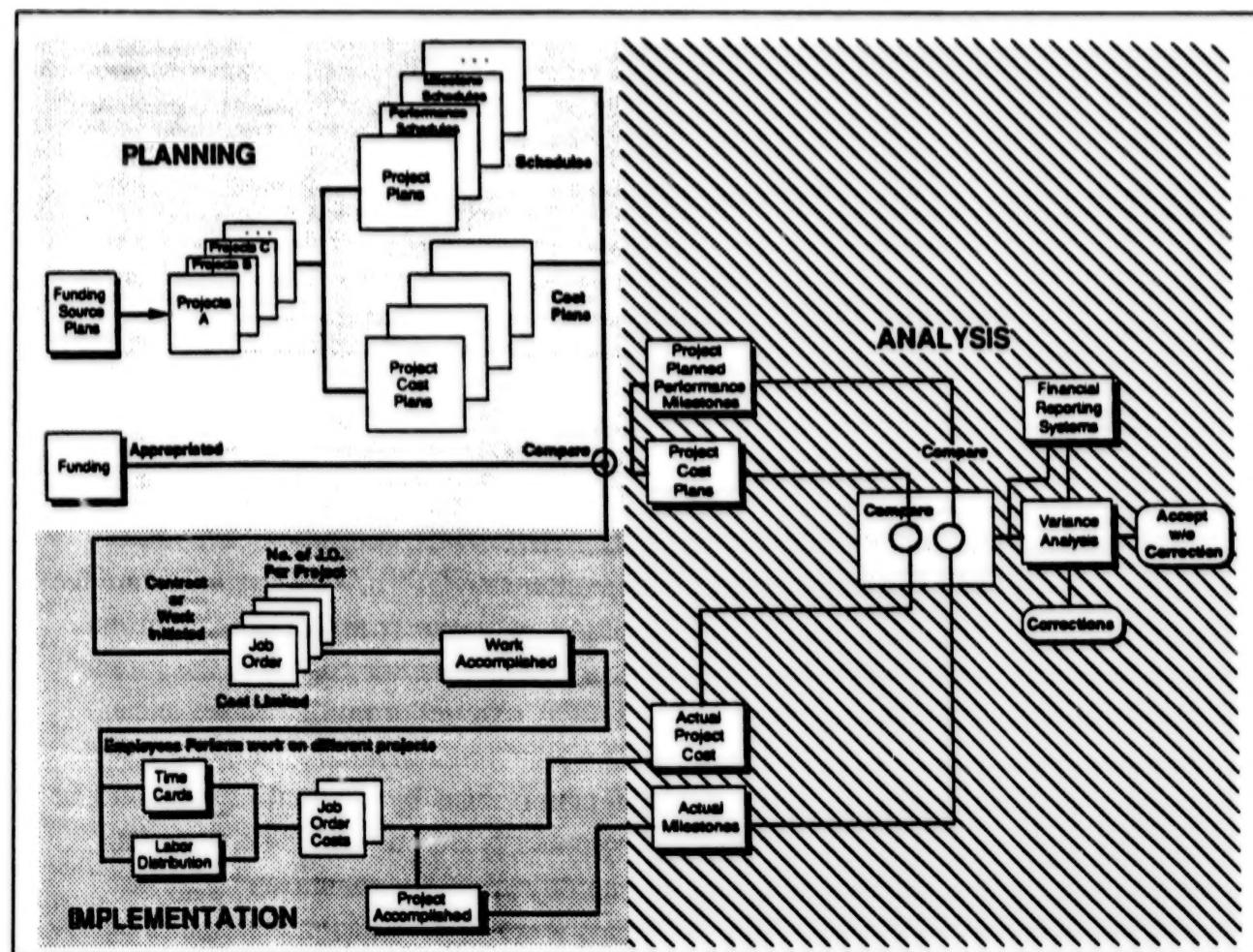


Figure 3. Generic Cost and Performance Model

XXX for an overall project fund source. The project may then be divided into subsets, each of which will be assigned a five digit UPN XXX-YY. These subsets may be further divided and funded with a seven-digit UPN XXX-YY-ZZ. Figure 3 represents the generic flow in the planning, implementation and analysis of cost and performance within STL at SSC.

These funding sources (UPNs) represent the dollar amounts assigned to the project from the various headquarters organizations. It further represents the overall results of the budgetary cycle within the organization or agency for the fiscal year. Thus, given the dollar amounts assigned to the UPNs, the project planning cycle can begin. Cost plans for individual projects are developed for specific elements of cost and spread across the

fiscal year. A typical cost plan is shown in Figure 4.

The elements of cost are the classical labor, materials, equipment and other direct costs (ODC). Also included are the subsets of labor (straight time, overtime, etc.), subcontractor cost and the subsets of ODC (travel, training, bases, etc.). The plan "cost elements" and the report of actual costs by the contractor should be completely compatible. The cost plan should reflect the manpower required each month, the anticipated cost of equipment or materials and projected travel and training and other costs as listed. The cost plan is, at best, just a plan. It should have adequate schedule slack and budget contingency to solve inevitable problems along the way (Longanecker, 1990). It and the elements of cost can be and should be adapted to

the types of cost one may incur in any specific project. There may also be unique costs. Within STL, for example, aircraft missions flown to collect remote sensing data for scientific research and development projects are one important cost that is planned, tracked and reported by either the contractor or government personnel as "aircraft missions."

At the top left of the STL Project Plan is the UPN number (551-20-00) for this project. The UPN may support more than one project; therefore, this project is assigned a benefitor code (BF) of VVB. Each project has assigned a benefitor code which is directly related to a UPN. The next item on the top left side is the project name (SIDS/IDS). SIDS/IDS stands for the Shuttle Ice Detection System, a subset of the Infrared Detection Systems being developed at SSC. The final description is the crew/depart. The Technology Development Division within STL is responsible for the project and has a department number of HA20 designated by 20 on the form.

On the top right side is the financial status at the beginning of the fiscal year when the

plan is initially developed; the uncotted carry-over, new obligation authority, total available to cost and planned carry-over.

The actual work tasks represented in the elements of cost are scheduled in the performance milestone plan. Figure 5 is a typical milestone chart for a particular project. The project tasks are listed, and expected completion dates are spread across the fiscal year by month.

The cost plans and milestone schedules are necessarily prepared at the beginning of the fiscal year. They are the basis for planning resources across the organization. This includes, but is not limited to, personnel staffing, skill mix, procurement plans, training budgets, travel budgets and office space requirements. Actual monthly costs are compared with the plans and any significant variance ($\pm 10\%$) is explained. Knowledge of this variance and the explanation for it allow the project manager to make the necessary adjustments to keep the project on schedule and within budget. Therefore, the first step in CAPS is planning.

Mid-Year Update													
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	TOTAL
UPN: 551-20-00													\$0
BF Code: VVB													\$0
Project: SIDS/IDS													
Contractor: LESC													
Crew/Dept: 20 (TDD)													
Uncotted Carry Over (Prev. Year): \$450,782													
New Obligation Authority (Current Year): \$0													
Total available to Cost: \$450,782													
Planned Carryover (1st Quarter '92): \$0													
Commitments:													\$0
Obligations:													\$0
Labor:													
- Straight Time													
- Overtime													
- Shift Differential													
- Q/T Premium													
Actual Labor Cost:	\$0	\$0	\$0	\$0	\$0	\$26,409	\$4,836	\$4,836	\$4,836	\$4,835	\$4,835	\$4,835	\$53,509
													\$1,823
TOTAL LOADED LABOR:	\$0	\$0	\$0	\$0	\$0	\$40,888	\$7,487	\$7,487	\$7,487	\$7,486	\$7,486	\$7,486	\$85,807
Subcontractor Cost:													\$0
LOADED SubC. Cost:	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Equipment:													
LOADED Equipment:	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$310,000
													\$310,000
Materials:													
LOADED Materials:	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$352,916
													\$352,916
ODC:													
- Travel/Training													
- A/C Missions													
- Services/Seasied													
Total ODC	\$0	\$0	\$0	\$0	\$0	\$1,439	\$5,578	\$0	\$2,277	\$0	\$2,277	\$0	\$10,164
													\$0
Totals for Month:	\$0	\$0	\$0	\$0	\$0	\$42,327	\$13,065	\$7,487	\$9,764	\$7,486	\$10,049	\$360,604	\$450,782
Cum. Month Totals:	\$0	\$0	\$0	\$0	\$0	\$42,327	\$55,392	\$62,879	\$72,643	\$80,129	\$90,178	\$450,782	\$450,782

Figure 4. Project Cost Plan

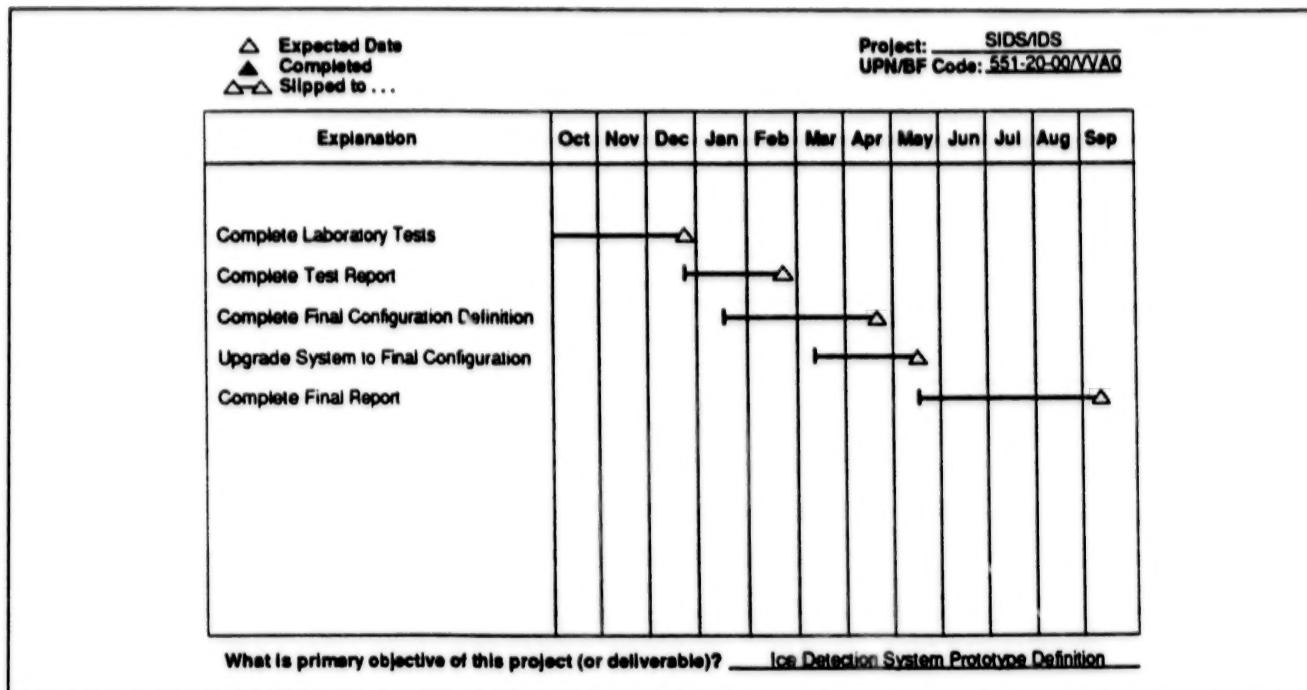


Figure 5. Milestone Schedule

The Science and Technology Laboratory has in any one fiscal year 60-65 fund sources (UPNs) at the seven-digit level. These are broken out into 164 benefactor codes (separate projects) which are planned and scheduled in detail by 40 project scientists and engineers.

The planning process starts approximately three weeks prior to the end of the fiscal year (September) and is completed one week prior to the first fiscal month (October). The cost plans and milestone schedules are formulated and put in place to track cost and performance. At STL, they remain unaltered (not changed) until midyear. At midyear the plans are updated to project the remaining work over the April/September timeframe. These plans are projected based on what occurred in the first six months, what is remaining to be done and what resources are available for the second half of the fiscal year. Other agencies may require adjustments more frequently, depending on the projects and stability of the fund sources.

The planning process is completed when the project tasks and the necessary dollars to accomplish those tasks are realistically scheduled across the fiscal year. The planning portion of the generic cost and performance model of Figure 3 is contained in Figure 6. After the planning phase, the organization proceeds with the implementation phase.

Implementation Phase

To implement CAPS, it is necessary to establish a structured mechanism for assigning work tasks that can be directly associated with the "lowest" designated funding source. A "work order" provides the authority to apply resources, (human, physical and financial) to accomplish the tasks required to support the project. Each work order must be accounted for in the Project Cost Plan (Figure 4). The work order includes more than just the tasks to be accomplished. It also includes the schedule for completion, deliverables expected, the dollar limit and the suborganizations or shops involved in the work.

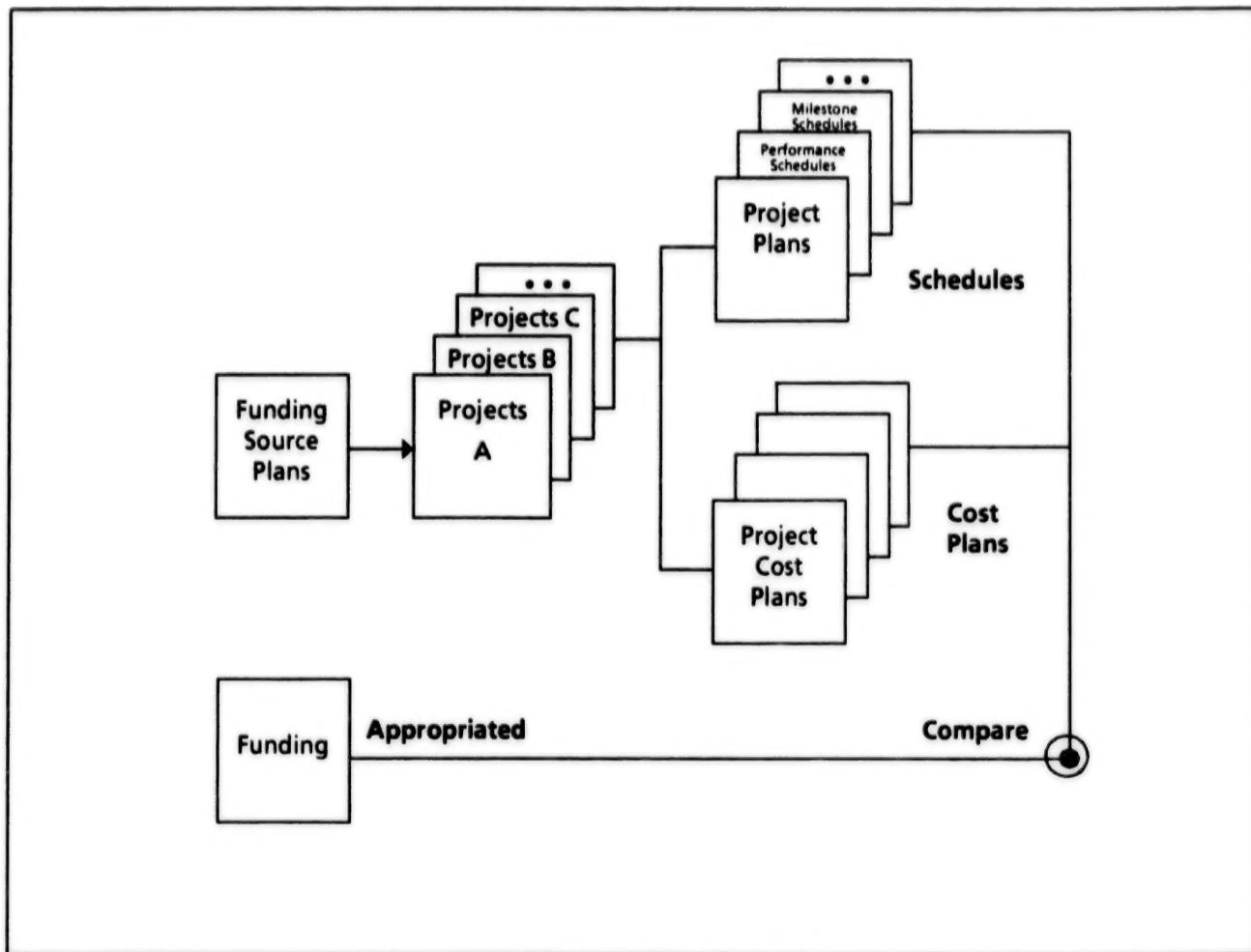


Figure 6. Planning Process

In a customer/contractor arrangement as occurs within Federal agencies, the contract document provides insight into the mechanisms used to initiate work. For example, in the SSC government contractor environment, work requests take the form of job orders (JOs) for the research contractor; facility service requests (FSRs) for the facility support contractor; and technical work requests (TWRs) for the technical services contractor. The format used by STL is the job order as shown in Figure 7.

Any number of work requests or job orders may be required to carry out any one project. These are identified by the JO numbering system, which is directly related to the projects and organization. Some intelligence has

been built into this system in that the first three letters of the job order number are the benefactor code (funding source). The fourth and fifth numbers are simply the sequence number and the sixth and seventh numbers are the division number from which the job order originates.

For example, a job number at STL is VVD.01.20; where VVD is the benefactor code, 01 is the sequence number and 20 indicates that the job order originated in the HA20 division. This numbering system provides a mechanism for tracking personnel and equipment charges. Personnel time cards and labor distribution sheets reflect job order charges. These records are the fundamental database for the subsequent accumulation of

NASA National Aeronautics and Space Administration John C. Stennis Space Center					SUPPORT CONTRACTOR JOB ORDER	DATE 10/15/90
					CONT. CONTROL NO.	
CONTRACTOR LESC	ORIGINATOR Penton	EXTENSION 1932	DIVISION H400	NASA CONTRACT NO. NAS13-315		
TASK & JOB ORDER NO. CSBO-07-01	CONTRACTOR PROJECT NO. 018-CSBO7			ACCOUNTING CODE NO.		
TITLE PRESENTATION GRAPHICS						
DESCRIPTION						
<p>Background: Graphic arts services are required to produce materials required for briefings of general, non-project topics. Only such generic, all-STL topic materials should be produced on this job order. Where there is doubt as to the scope of the requested support, the Technical Monitor, or identified alternate(s) should be consulted. In many cases, materials must be produced and modified on short notice, thus establishing the need for the capability to respond to "quick-reaction" requests.</p>						
<p>Tasks:</p> <ol style="list-style-type: none"> Maintain necessary graphic arts supplies and equipment to support this job order. Maintain a file of reproducible masters of graphics, purging file as requested by technical monitor. Produce graphic arts in response to requests from STL technical monitor. Coordinate and monitor any graphics work sent to other SSC contractors. Provide oversight to cost-effective operation of graphic functions and recommend changes to technical monitor as appropriate. Maintain adequate records so that technical monitor will have immediate and full insight in deliverable schedules. Such schedules are to be established when individual graphic arts tasks are accepted. 						
<p>Schedules: As established when individual tasks are accepted.</p>						
<p>Deliverables:</p> <ol style="list-style-type: none"> Graphic arts products as specified when requested. Full records of production in weekly activity report. Other records of production when audits are required. 						
<p>Cost of J.O. not to exceed \$19,608.</p>						
RESOURCES REQUIRED				SCHEDULE		
EST. CONTRACTOR MANHOUR REQUIREMENTS 846			EST. BEGINNING DATE 10/1/90	EST. COMPLETION DATE 7/31/91		
EST. MATERIAL COST	TOTAL EST. COST \$19,608		DATE COMPLETED	SIGNATURE		
CONTRACTOR COORDINATION		DATE	NASA CONCURRENCE/APPROVAL		DATE	
SECTION SUPERVISOR			TECHNICAL MONITOR			
TECHNICAL SUPERVISOR			TECHNICAL MGR'S REP			
PROGRAM MANAGER			GROUP CHIEF			
DISTRIBUTION			PAGE	OF	PAGES	

Figure 7. Job Order Form

project costs. As the work is accomplished, charges (costs) are made to the job order. These charges are reflected in the cost plans as illustrated in Figure 4.

An individual monthly job order report is furnished by the contractor. A sample report from STL is shown below in Figure 8.

JOB ORDER REPORT FOR THE MONTH OF JUNE		
RUN DATE 06/28		JOB ORDER TOTAL \$ 300,782
JOB ORDER VVBO.01.20 Ice Detection Prototype		
	YEAR TO DATE ACTUALS	CURRENT MONTH ACTUALS
Hours		
ST Hours	1836.9	158.6
OT Hours	131.2	0.0
Total Hours	1968.1	158.6
MYE		
ST Labor	1.3	1.1
OT Labor	0.0	0.0
Total MYE	1.4	1.1
Cost		
ST Labor	\$41,819	\$ 4,192
OT Labor	2,665	0
Shift Diff	0	0
OT Premium	15	0
Total Cost	\$44,499	\$ 4,192
Overhead	\$16,100	\$ 1,551
Subcontracts	\$ 0	\$ 0
Equipment	\$ 40	\$ 0
Material	\$ 2,760	\$ 0
OTHER DIRECT COST		
Travel	\$ 4,469	\$ 742
Services/Leases	2,916	3
Relocation	0	0
Use Tax	188	124
Total ODC	\$ 7,573	\$ 869
Total Cost Before G&A	\$70,972	\$ 6,612
G&A	\$ 4,258	\$ 397
Cost of Money	\$ 50	\$ 5
Total Cost Before Fee	\$75,281	\$ 7,013
Fee	\$ 4,483	\$ 425
Indirect Cost	\$ 0	\$ 0
TOTAL COST	\$79,764	\$ 7,438
OBLIGATIONS		
MATERIAL/EQUIPMENT	\$ 9,927	
TRAVEL	\$ 0	

Figure 8. Job Order Report

Similar to the cost plans, the job order report is broken into cost elements and shows the monthly data as well as Year-to-Date (YTD) data. If a principal investigator or project manager has multiple job orders under one benefitor, in various suborganizations or

shops, the activities and tasks can be accomplished as well as costs in the different areas.

The cumulative costs for the benefitor are shown in the contractor's 533M (Monthly) Report, shown below in Figure 9.

BENEFITOR CODE REPORT FOR THE MONTH OF											
RUN DATE 06/29		June			COST PLAN DATE 04/17/91						
BENEFITOR CODE VVBO SIDS/IDS											
HA20 SPIERING											
LABOR	YEAR TO DATE BUDGET	YEAR TO DATE ACTUALS	O/U VARIANCE	CURRENT MONTH BUDGET	CURRENT MONTH ACTUALS	O/U VARIANCE					
Hours											
ST Hours	1883.1	1836.9	-46.2	254.5	158.6	-95.0					
OT Hours	91.2	131.2	40.0	0.0	0.0	0.0					
Total Hours	1974.3	1968.1	-6.2	254.5	158.6	-96.9					
MYE											
ST Labor	1.4	1.4	0.0	1.8	1.1	-0.7					
OT Labor	0.1	0.1	0.0	0.0	0.0	0.0					
Total MYE	1.5	1.5	0.0	1.8	1.1	-0.7					
Cost											
ST Labor	\$39,094	\$41,819	\$ 2,725	\$ 4,836	\$ 4,192	\$ -644					
OT Labor	1,841	2,665	824	0	0	0					
Shift Diff	0	0	0	0	0	0					
OT Premium	12	15	3	0	0	0					
Total Cost	\$40,947	\$44,499	\$ 3,552	\$ 4,836	\$ 4,192	\$ -644					
Overhead	\$14,882	\$16,100	\$ 1,218	\$ 1,789	\$ 1,551	\$ -238					
Subcontracts	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0					
Equipment	\$ 40	\$ 40	\$ 0	\$ 0	\$ 0	\$ 0					
Material	\$ 81	\$ 2,760	\$ 2,679	\$ 0	\$ 0	\$ 0					
OTHER DIRECT COSTS											
Travel	\$ 8,164	\$ 4,469	\$ -3,695	\$ 2,000	\$ 742	\$ -1,258					
A/C Missions	0	0	0	0	0	0					
Services/Leases	48	2,916	2,868	0	3	3					
Relocation	0	0	0	0	0	0					
Use Tax	10	188	178	0	124	124					
Total ODC	\$ 8,223	\$ 7,573	\$ -650	\$ 2,000	\$ 869	\$ -1,131					
Total Cost Before G&A	\$64,173	\$70,972	\$ 6,800	\$ 6,625	\$ 6,612	\$ -2,013					
G&A	\$ 3,850	\$ 4,258	\$ 408	\$ 518	\$ 397	\$ -121					
Cost of Money	\$ 46	\$ 50	\$ 5	\$ 6	\$ 5	\$ -1					
Total Cost Before Fee	\$68,069	\$75,281	\$ 7,212	\$ 9,149	\$ 7,013	\$ -2,136					
Fee	\$ 4,130	\$ 4,483	\$ 353	\$ 490	\$ 425	\$ -65					
Indirect Cost	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0					
TOTAL COST	\$72,199	\$79,764	\$ 7,565	\$ 9,639	\$7,438	\$ -2,201					
OBLIGATIONS											
MATERIAL/EQUIPMENT	\$ 9,927										
TRAVEL	\$ 0										

Figure 9. Benefitor (533M) Code Report

The 533M report is a requirement levied on the contractor by the government. Contractors must provide a monthly summary of costs for the current month and YTD costs for each project (benefactor). This monthly cost summary (533) has basically the same elements of costs as the cost plans. The only difference is the contractor overhead, G&A and fee statements. The current month's budget, current month's actual cost and variance are listed in the right three columns. The YTD budget, YTD actual cost and variance are listed in the left three columns next to the elements of costs. Project managers must understand the variance column of this report in order to judge performance of the contractor.

At this point in the generic model, the implementation phase is complete. This process is shown in Figure 10. The subsequent phase is the analysis of the data on a monthly basis.

Analysis Phase

The analysis phase of the process provides the analysis of the actual against the planned cost and scheduled milestones data. This comparison results in a difference of planned versus the actuals called "variance." Analyzing these comparisons results in conclusions relative to project performance. The results are then compared in the cost and schedules milestone matrix in Figure 11.

The cost analysis results in a cost underrun, on-target or overrun. Schedule milestones analysis provides under achievement, on-target, or over achievement. The combination of these two sets of parameters yields a performance indication.

The purpose for the variance analysis is to provide an understanding of trends or implications of performance to reduce management surprises and enable early corrections.

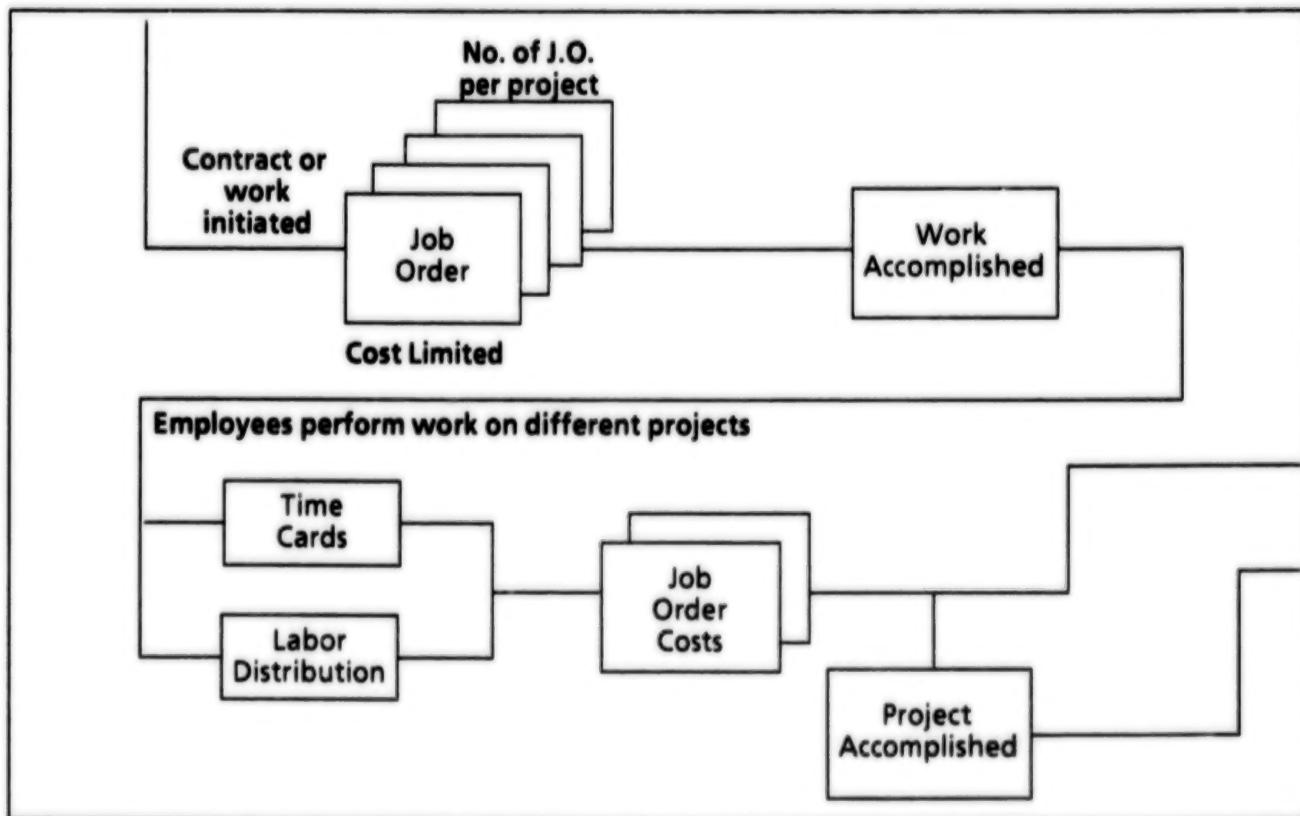


Figure 10. Implementation Phase

The matrix in Figure 11 provides the combination of cost and scheduled milestone accomplishments that translate into performance. Performance is an indicator of productivity reflected in the planning of work and its associated dollars, and measurement of actual accomplishments and costs.

COST	SCHEDULED MILESTONES		
	<i>Under Achieve</i>	<i>On Target</i>	<i>Over Achieve</i>
<i>Underrun</i>	Questionable	Good	High
<i>On Target</i>	Weak	Good	High
<i>Overrun</i>	Poor	Weak	Questionable

Figure 11. Performance Matrix

The analysis of the performance matrix indicates the "underrun of cost" row is the best performance posture except in the case of under achievement of milestone accomplishment. The under achievement of milestones accomplishment and underrun of cost is a lack of performance based on the dimension of time and milestones scheduled. This underrun condition may indicate potential problems or significant cost overruns. The remaining performances in the "cost underrun" row go from good to high performance when meeting or exceeding the scheduled milestones.

The "on-target cost" row proceeds from weak to good and finally to high performance with under achievement, on-target, and over achievement of scheduled milestones. The "cost overrun" row provides a poor, weak or questionable performance when transcending from under achievement, on-target and over achievement of scheduled milestones.

The relative degree of high, good, weak, poor and questionable performance can be determined as a consequence of the detailed analysis of cost and scheduled milestone data. Examining these elements and questioning the variances from project plans provides ex-

tensive insight as to the absolute magnitude of performance. With the actual costs in the accomplishment of planned tasks, these costs can be examined at the data entry level of the personnel time card and labor distribution sheet at the job order or work request level during detailed analysis or anomaly resolution.

From the initial planning, changes in projects can and will occur. However, the initial cost plan was constructed from the original planned milestones and schedules. While maintaining the original plans, the rationale and reasonableness of variation between what was planned and what actually occurs can be assessed and determined. From this baseline, the analysis and variance explanation is understood and may be accepted without correction to the project.

A project correction may require redistribution of resources, application of additional resources, resolution of problems, etc. Acceptance without correction requires an understandable explanation of the differences in cost expenditures and achievement of milestones from what was initially planned.

Understanding that plans of all types are subject to change, the initial planning in this context is held constant for the first six months of the fiscal year. At midyear, the cost plans and milestone schedules are readjusted for the remainder of the fiscal year. The project carryover (planned and unplanned) into the next fiscal year is noted and tracked for continuity and used in establishing a credible plan for the next year. Having contingency funds available covers any uncertainties of project dollars into the new fiscal year.

The cost plans, cost actuals and milestones/schedules, both planned and actual, are documented and aggregated at the project level, then to the fund sources level in the Financial Reporting Systems (Figure 12).

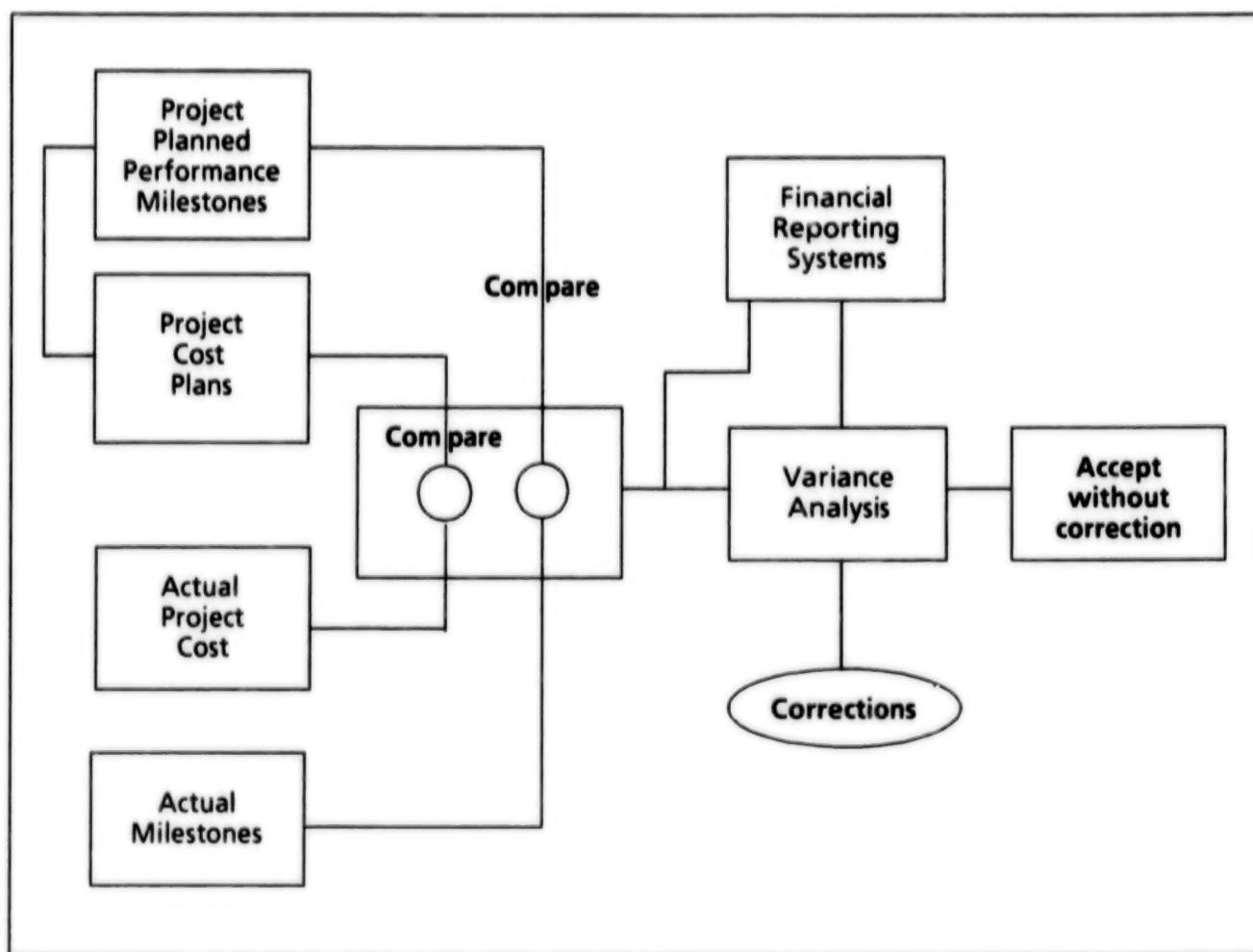


Figure 12. Analysis

Documentation

The records of plans and actuals from the detailed level through the aggregation at the division level, directorate level, Center level and finally a summary to the Headquarters level, constitute documentation of CAPS. All data, regardless of the level of summary or details, are definable to the lowest level in the process. Variance explanations are summarized and carried through all levels of aggregation.

Summary

CAPS is an automated system used from the planning phase through implementation to analysis and documentation. Data is available or retrievable for analysis of cost versus performance anomalies. CAPS provides a uniform system across intra- and inter-organizational elements. A common system

is recommended throughout an entire cost or profit center. Data can be easily accumulated and aggregated into higher levels of tracking and reporting of cost and performance.

For effective program management and control to exist, an environment of accountability of organizational elements and individuals must exist. The implication is that the level and quality of performance or productivity is indicated in the CAPS model and its process. Management overview and the monthly reporting and analysis provides a mechanism for management change, redirection or support of the project's progress.

The CAPS model provides the necessary "decision" information and insight to the principal investigator/project engineer for a successful project management experience. In

fact, CAPS provides all levels of management with the appropriate detailed level of data.

The CAPS model is a disciplined process for obtaining required feedback necessary for measuring performance on programs and projects. It is recommended for cost and performance tracking for any size or number of projects. The results indicate productivity/performance and successful project management.

CAPS has been implemented utilizing different software and hardware systems. It is currently residing on a PC-based system and an institution minicomputer. The concept and

system are adaptable to any high level database and project networking software. Depending on the number of projects, in most cases CAPS can be handled by PC hardware and software.

The CAPS model provides for planning, implementation, analysis and tracking of projects. Projects utilizing this system at SSC range from several thousand dollars a year to over a million dollars per year. SSC also uses the system for multimillion dollar projects. The principal investigator or project engineer has the responsibility and authority to implement the project. CAPS provides a consistent and uniform system to plan, implement, analyze and track a project.

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PLANNING AND SCHEDULING FOR SUCCESS

by Ignacio Manzanera, CCE

Planning and scheduling should be performed according to the kind of organization and project you have at hand. Selecting the ideal planning and scheduling environment for your business may give you the competitive edge. This paper presents the reference information required for setting up the most convenient planning and scheduling (P&S) system and provides useful reference tables to assist the user decision-making at critical milestone dates. The four sections of the paper are:

1. Understanding planning and scheduling and their role in the capital projects environment.
2. Recognizing the importance of early P&S and the need to develop your project accordingly. We should realize the need to measure results, evaluate changes, train newcomers, keep historical data, control costs, establish financial constraints and constantly improve cost and time estimates.
3. Respecting human factors in the P&S development cycle, the common denominator of consolidated business success. The key roles are played by teamwork, professionalism and discipline in capital projects development.
4. Planning and scheduling development, routines, presentation and the selling of a product.

Understanding Planning and Scheduling

Some project people think of planning and scheduling as yet other management requirements to be complied with. They do not even differentiate between the two functions and consequently fail to see their value as tools for measuring results, evaluating

changes, training new employees, keeping historical data organized, controlling costs and time and establishing financial needs.

Planning is an innate human trait that allows everyone to visualize what has to be done and to proceed accordingly. This may be easy to do when the project in mind is something that does not contain more than 20 activities. Beyond that boundary, most of us will need to make a list of all the activities and possibly their sequential order to ascertain the accomplishment of all of them.

A list may not be enough when the number of activities becomes more than 100 and the necessary resources have to be accounted for. A management procedure, usually accompanied by a computer system, may be the only way to visualize the total work and to communicate it to the rest of the project team.

Table 1.
Checklist for Project Planning Basics

- | |
|---|
| <ul style="list-style-type: none"> ● Construction equipment availability ● Work site conditions and storage place ● Construction duration and expected weather conditions ● Performance expected constraints ● Procurement market status and expected trends ● Labor availability and expected productivity ● Temporarily needed utilities ● Local bylaws, studies and interpretation |
|---|

The primary planning objectives are concerned with getting things done within the shortest available period of time, minimizing cost and risk, and complying with the required technical specifications. Table 1 shows the basic subjects that should be addressed by project planners.

Table 2 lists the elements needed to achieve desired results.

Table 2. Planning Elements

- | | |
|---------------|--|
| ● Objective: | Goals/target/quotas to be accomplished |
| ● Program: | Strategy to be followed |
| ● Budget: | Resources and expenditures organized logically |
| ● Forecast: | Projections of what is going to happen |
| ● Policy: | Guidance for decision-making |
| ● Procedures: | Detailed methods for carrying out a policy |
| ● Standard: | Accepted performance level |

Scheduling is a management tool that provides time and other resource allocation to previously designed plans. Scheduling is one of the simplest and least sophisticated tools available to project management. With a good team effort at the beginning of the job and undivided support, it can be a powerful project control tool. Table 3 presents a checklist for project scheduling basic activities.

Table 3.
Checklist for Project Scheduling Basics

- | |
|---|
| ● Set up a work breakdown structure (WBS) |
| ● Interface the organization breakdown structure with the WBS |
| ● Sequentially organize project activities |
| ● Run critical path calculations and establish project duration |
| ● Establish a progress measuring system |
| ● Communicate results, reviews and revisions |

Unfortunately, scheduling is usually neglected by management because of the level of complexity that it typically requires.

Recognizing the Importance of Early Planning and Scheduling

P&S should start at the project conceptual stage, for obvious reasons. Some of them are discussed below.

Maintaining Solid and Consistent Cost Estimates. Enforcing P&S from project inception ensures that everyone within the organization will be aware of what is taking place. Participation becomes more effective; cost estimates are comprehensive and accurate.

Designers' communication with the rest of the team becomes a question of simply updating plans and schedules and distributing them. Cost estimators will have a clear idea of the scope of the job, regardless of how many changes take place during the development of the project.

Designers will feel comfortable knowing that cost and time estimates are faithful representations of what they are designing. Cross checking the estimators' work is made easy by following the work breakdown structure and logic sequence of events created by using P&S. The real reward comes from having a tool that keeps the project team working purposely for a common objective.

Instant Evaluation of Changes. There is nothing more distressing when working on a project than the inability to efficiently evaluate change in the project design or establish a comparison between two alternative courses of action. P&S provide effective means to know which areas of the project are bound to be affected by the decision. Total project expected impact in terms of cost and time are immediately evident. Again, all project members will be able to visualize the proposed situation and make valuable contributions.

Establishing Financial Needs. When cash flow and other financial implications for the project can be established at an early stage in the project, designers have a better chance to come up with the right ideas. The cash flow usually dictates what can be done and when. It would be silly to ignore this fact when designing and planning a project. P&S provide a clear path of expenditures through the expected project life. Management has little problem understanding the project financial needs and matching the required cash flow to the plans.

Measuring Results. Knowing where the project stands at all times is essential for productivity, cost control, future commitments, coordination and morale. Some people are scared of P&S because they think they look bad when they do not perform exactly as planned. Plans are seldom followed to the letter; they provide an excellent tool to target effort exactly as planned.

Storing Historical Data. Gathering information for future reference is an endeavor always pursued by organizations that are in the business and want to continue being part of it. P&S supplies a systematic and organized tool to keep records of project developments. Original plans and schedules and the revised ones provide the sequence of events that took owner, designer and contractor to the final product. Future project planning, scheduling, cost estimating and financing of similar projects will have a backup reference to guide their development.

Training Newcomers. Through the first stages of its life cycle, a project continually builds up labor levels. The introduction of newcomers to project scope and status could be extremely easy if P&S has been running from the beginning of the project. Original plans, propositions, changes, updates, analysis and the like will be registered on the achieved schedule revisions. Visualization of the project status is available at all times.

Human Factor Analysis

Bookstores are flooded with books describing successful business ventures and the reasons behind them. A common denominator among them is "teamwork." A project team is a group of persons with different backgrounds working for a unique objective, the successful completion of a particular project. It is essential for all members of a project to work as a team, contribute their expertise, share all information and maximize resource utilization.

Owners, designers and constructors may have different ideas about their functional goals, but when they work together as part of a project management team, they must understand their jobs as members of this unit. If the project team's objectives statement is wrong, everything that follows will be wrong, too. Starting with a clear understanding is essential.

People in project teams usually know their job descriptions, their benefits package, and their own job objectives. But their ideas about the project team's mission are frequently vague. As a group, project team members may never have articulated their objectives to one another. P&S makes everyone in the project team realize the importance of:

- Understanding their job as part of a team.
- Having a clear idea of the project objectives and how the team, as a group, is pursuing them.
- Identifying critical milestones to be reached and the expected contribution from the team members.

P&S fosters team member communication and interfaces, clarifies assumptions about leadership, encourages competition, guides reward systems and enhances probabilities of success. Other team-related skills such as flexibility, patience, ability to check out as-

sumptions, willingness to listen to others, curiosity and versatility are encouraged by P&S among project team members. P&S educates project managers to trust the ability of effective teams to outperform individuals.

Planning and Scheduling Development

The key issue in selecting a P&S working package is simplicity. It must be kept in mind that for a P&S program to work, it must be clearly understood by all. If it is confusing, it will not be followed; and if it is not followed, people will not make the necessary effort to make it accurate, and consequently, it will become useless.

Reports must be kept short so anybody can read them, and graphics must be abundant so people bear in mind what is going on. Needless to say, accuracy should be consistent so that everybody in the project is guided by the P&S program. Different project forums should use different levels of detail. It would be a useless exercise to try to expose management to all schedule calculations. This belongs to the planning and scheduling engineers. By the same token, it would be ridiculous to think that engineers can manage all aspects of a job using a simple bar chart.

P&S Needs at Project Conceptual Stage. The main activity for P&S at project conceptual stage is identification of the scope of the job. (Table 4). It means that every input by the conceptual engineers must be translated

Table 4. Checklist for P&S Activity at the Conceptual Stage

- Gain total project management team commitment on the P&S program.
- Establish update periods, feedback deadlines, level of detail and distribution list.
- Decide on computer applications to use.
- Identify scope of work.
- Generate a work breakdown structure.
- Introduce first P&S program draft and clearly establish its expectations.

to activities to be planned and scheduled. Once all activities have been identified, the work breakdown structure must be established to keep the work systematically organized. Finally, a master milestone schedule must be developed to help the team visualize the total project.

P&S at Project Proposal Stage. Project proposal development brings more detail to the plans, and it should be inserted into the incipient P&S program (Table 5).

Table 5. Checklist for P&S Activity at the Project Proposal Stage

- Set up the OBS.
- Define the OBS and WBS interface.
- Generate project code of accounts.
- Create work packages.
- Introduce a project proposal progress measuring system.
- Develop the first network schedule and update it periodically according to new information generated by the project proposal progress.
- Resource load the plan and schedule and identify long lead time material and equipment.

An organization breakdown structure (OBS) should be set up to establish management responsibility. Then, by interfacing the OBS with the WBS, working packages are set up. A breakdown of the work packages into cost items will provide the basis to develop the schedule network that will guide the project. An improved P&S program will help develop a better understanding of the scope of the job and generate more accurate cost/time estimates. Long lead time material required for the project must be clearly identified and scheduled according to the network plan.

P&S During Definitive Design. When project expenditures have been approved and definitive design is awarded, all the P&S effort developed during the previous project life phases will start paying off. Having a well

identified and organized schedule network with the solid foundations of WBS, OBS and work packages, planning and scheduling the definitive design phase will not be a problem. Table 6 presents a checklist for P&S efforts during the design phase.

Table 6. Checklist for P&S Activity at the Design Stage

- Compare inhouse schedules against awarded contractor schedules and revise accordingly.
- Set up a reliable project progress measuring system based on the approved working schedule.
- Revise the company's cost and schedule estimates as the design progresses to show the detail is continuously introduced and its corresponding impact on the plan.
- Keep a vivid interest on project procurement requirements and their impact on the job.

The number of drawings per cost item can be forecasted and labor levels established and compared against bidders' offers. A definitive design contractor's working schedule can be reviewed and approved accordingly and a progress measuring system implemented. The project's overall P&S should be constantly revised according to authorized-for-construction-drawing production. Time and cost estimates are adjusted against the latest materials and other resources takeoff lists, and P&S will provide a clear organization for everybody to visualize project status. Special attention must be given to planning and scheduling requisitions and purchase orders for long lead time material and equipment at this stage.

P&S During Construction. This final phase of the project will receive most of the benefits of the early P&S program. At the bid job explanation meeting there will be an in-house generated schedule network to help bidders understand what they are about to enter. It is an excellent tool for getting competitive bids and thereby cost reductions.

The previously developed cost items and work packages will provide a solid structure for bidders' quotation costing and avoidance of dear mistakes. Table 7 shows a checklist for P&S development during construction.

Table 7. Checklist for P&S Activity at the Construction Stage

- Compare inhouse schedules against awarded contractor schedules and revise accordingly.
- Set up a reliable project progress measuring system based on the approved working schedule.
- Update schedule resources allocation to ascertain that it matches the scope of the job and definitive cost estimate.
- Establish a project change processing procedure with emphasis of the approval cycle duration.
- Institute performance indicators to be utilized and clarify their interpretation.
- Review and revise activities working crew sizes and their qualification requirements.
- Establish early warning systems for cost and schedule slippages.
- Establish a direct line of communication between cost estimating, scheduling, material procurement and surveying, and make all of them responsible for the project outcome.

When bidders submit their proposals, their construction schedules can be cross-checked against the company's previously developed schedule for accuracy and scope compliance.

Conclusion

Planning and scheduling programs are excellent management tools when properly introduced to the project management team and regularly maintained. Communications, creativity, flexibility and accuracy are substantially improved by following a simple set of rules. A planning and scheduling program will work for you if you believe in it, make others in your project team realize its benefits, and above all, make it an extension of your project cost control philosophy.

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SCHEDULING: A GUIDE FOR PROGRAM MANAGERS

Defense Systems Management College

For 4,500 years after the building of the great pyramid at Giza, nothing surfaced as a better way to develop a schedule than that used for the pyramid. Then, early in this century, Henry L. Gantt, a pioneer in the field of scientific management, unveiled his bar chart technique. From that time forward, program planning and scheduling have consisted of a list of activities with start and completion dates.

Gantt's "daily balance chart" was a significant breakthrough. Suddenly, you could see at a glance the overall program schedule and the start and stop times of the program's individual components (Figure 1). A Gantt chart can be superimposed with ease on a calendar. Then, by shading in each bar as progress is made, a manager can easily measure actual progress against the schedule.

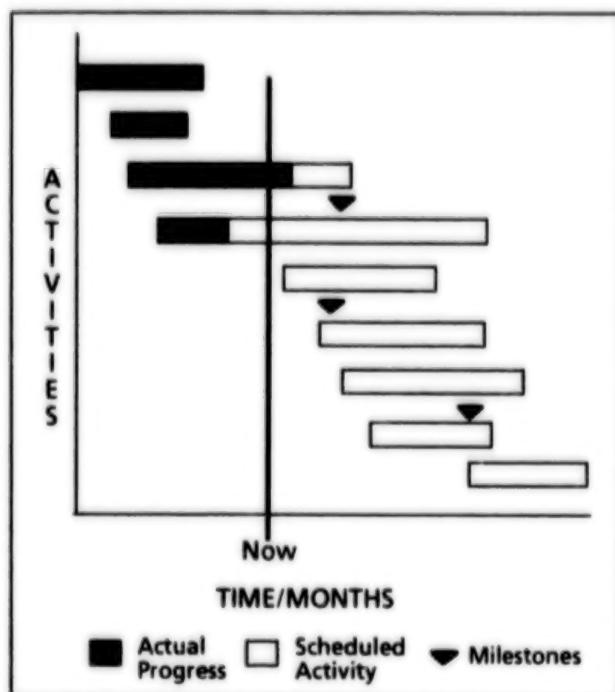


Figure 1. Gantt (Bar) Chart

For 50 years, bar charting was the best way to schedule activities. There were good reasons for it. Bar charts communicate, are easy to prepare and use, show key activities with specific start and completion times (scheduled and actual), relate schedules to calendar dates, and display days or weeks from program start to completion.

Figure 1 shows that milestones may be added to bar charts to display significant events. In fact, it may be appropriate to show a number of milestones associated with a single bar. Because they communicate so well and so quickly, bar charts are still used to plan and monitor progress against the plan. Upper management, in particular, appreciates this capability.

A shortcoming of bar charts is the limited information they portray. Dependency and other interrelationships among activities are difficult to display because bar charts handle a limited degree of complexity. Figure 2 shows how a bar chart can provide a clear, but limited, picture of dependencies and progress. The bar chart can present a history of changes and rescheduling occurring on a program; however, this is done more frequently on milestone charts, which will be discussed later.

As a scheduling tool, the bar chart is simple, communicates well, and displays calendar and significant program dates. Because of its simplicity and ease of interpretation, the bar chart is a particularly good tool for communicating important information to upper management; however, it is limited in the degree of detail and the interrelationships it can portray.

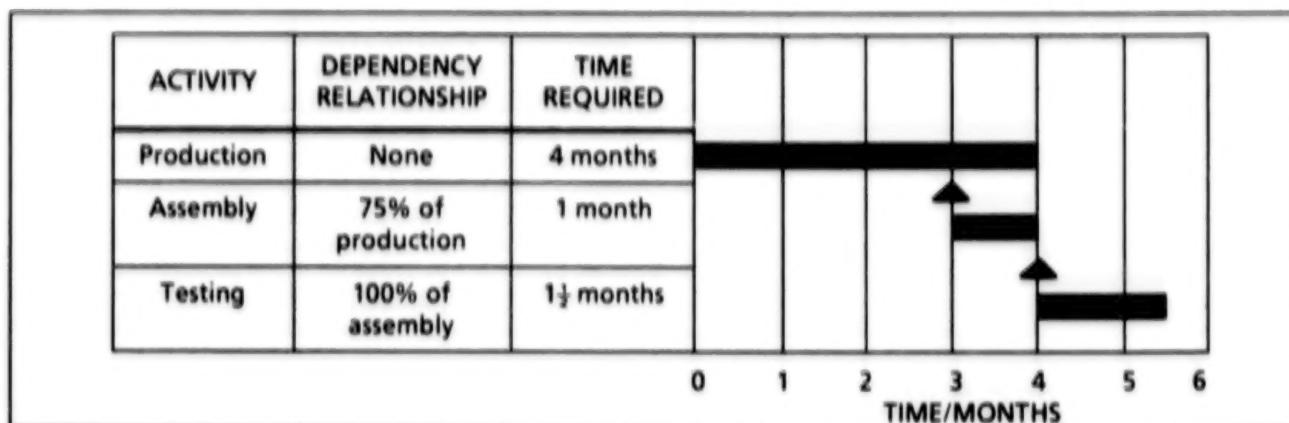


Figure 2. Gantt Chart Showing Dependency

Table 1 summarizes the strengths and weaknesses of Gantt charts. The weaknesses apply to planning, estimating and reporting as well as to bar charts.

Milestone Scheduling

Milestone scheduling is a popular technique

being used in Department of Defense (DoD) program management offices. The milestone chart is probably the most commonly used chart at the Air Force Systems Command, Electronic Systems Division (ESD), and many other DoD organizations. The technique is relatively simple. Milestone charts-

Table 1. Gantt Technique: Strengths and Weaknesses

CRITERIA	STRENGTHS	WEAKNESSES
1. Accuracy	Good in repetitive work. Time estimates are likely to be good and production is easy to count.	In non-repetitive work, accuracy of estimate of task completion percentage is subject to error.
2. Reliability	Simplicity of technique helps program manager to set up a consistent progress reporting system.	In repetitive work, production can be "doctored." Large non-repetitive programs involve many different progress estimators, which tends to affect consistency.
3. Simplicity	Easy to understand, accept and implement.	Requires good time estimates, or standards, which are not simple to develop.
4. Universality of program coverage	Effective at work-center levels. Cover a specific phase of program life cycle well.	Not effective for a large, complex program unless program is computer-based.
5. Decision analysis	N/A	No capability to stimulate alternatives.
6. Forecasting	Clearly shows ability to meet schedules in repetitive work.	Does not show ability to meet schedule if many interrelated tasks are involved.
7. Updating	Easy to update if program is static.	N/A
8. Flexibility	N/A	Much chart reconstruction needed to show program changes.
9. Cost	Data gathering and display are relatively inexpensive.	Frequent program changes cause costly redrafting of charts.

are event oriented, bar charts are activity oriented. For a particular program, a set of key events, or milestones, is selected. A milestone is a scheduled event that will occur when a particular activity is started or completed. Milestones are selected from the program management plan. By reviewing the status of key milestones, one can assess quickly the overall program status.

Although milestone charts can present more information than bar charts, they share one important drawback: they invite surprises. A surprise can occur when the number of displayed milestones is too limited or when interdependencies are not portrayed. The result may be that the program manager does not know the status of a key event until it occurs, or until it fails to occur when scheduled. A well conceived milestone status report can provide early warning of a potential problem, and early problem recognition is a key to successful program management.

The milestone scheduling technique uses a symbology consisting of arrows and diamonds, or similar designators, to show originally planned event dates and the changed dates. Figure 3 shows the symbols and their meanings used by the Air Force at ESD. Any symbol can be used; mechanics are not as important as principles.

Arrows are used to show rescheduled events; diamonds indicate the originally planned schedule. As a result, the milestone schedule allows us to improve on the Gantt chart by retaining the baseline dates, while incorporating changes in planned future events. Figure 4 is an example of a milestone chart.

The milestone chart records the manager's assessment. For example, a manager might reasonably predict that a one-month slip in the start of software development will probably result in a several-month slip in com-

pleting the engineering development phase. The milestone chart does not provide the assessment - the manager's experience does. This is the key to understanding the use of milestone charts. Unless the activity and interrelationships of milestones are understood, the chart tells only what has happened and what is yet to happen. However, by coupling historical information with the manager's experience and knowledge, more accurate predictions can be made.

The milestone scheduling technique shows what is scheduled, what has happened and changes in plans. The technique is not as useful for forecasting schedule changes as are the network and line-of-balance techniques discussed later.

Like the bar chart, the milestone chart is an effective method of communication. The symbology is relatively standard and simple to use. The chart presents actual progress against a baseline plan and displays changes in plans. The mechanics of constructing a milestone chart are relatively easy. Many defense contractors use milestone charts extensively in DoD program management.

As with simple bar charts, a major weakness of milestone charts is their inability to show interdependencies and interaction among activities. A potential problem can result if a program manager focuses on a relatively simple milestone format. He may lose sight of the complexity of the relationships among various program tasks.

Although milestone charts are used on complex programs, they are usually the product of network analysis. Milestone chart preparation is relatively simple, but developing and analyzing the information going into the charts can be time consuming. A controlled flow of accurate, timely and appropriate information is important.

Standard symbols have been adapted for Air Force milestone schedules. The most common symbols used and their meanings are shown below.

Basic Symbol	Meaning
◇	Schedule completion
◆	Actual completion
◊	Previous scheduled completion—still in future
◆	Previous scheduled completion—date passed
Representative Uses	Meaning
◊ ◇	Anticipated slip—rescheduled completion
◆ ◇	Actual slip—rescheduled completion
◆ ◆	Actual slip—actual completion
◆ ◊	Actual completion ahead of schedule
↑ → ↑	Time span action
↑ → →	Progress along time span
↑ → ↗	Continuous action

Figure 3. Milestone Symbols

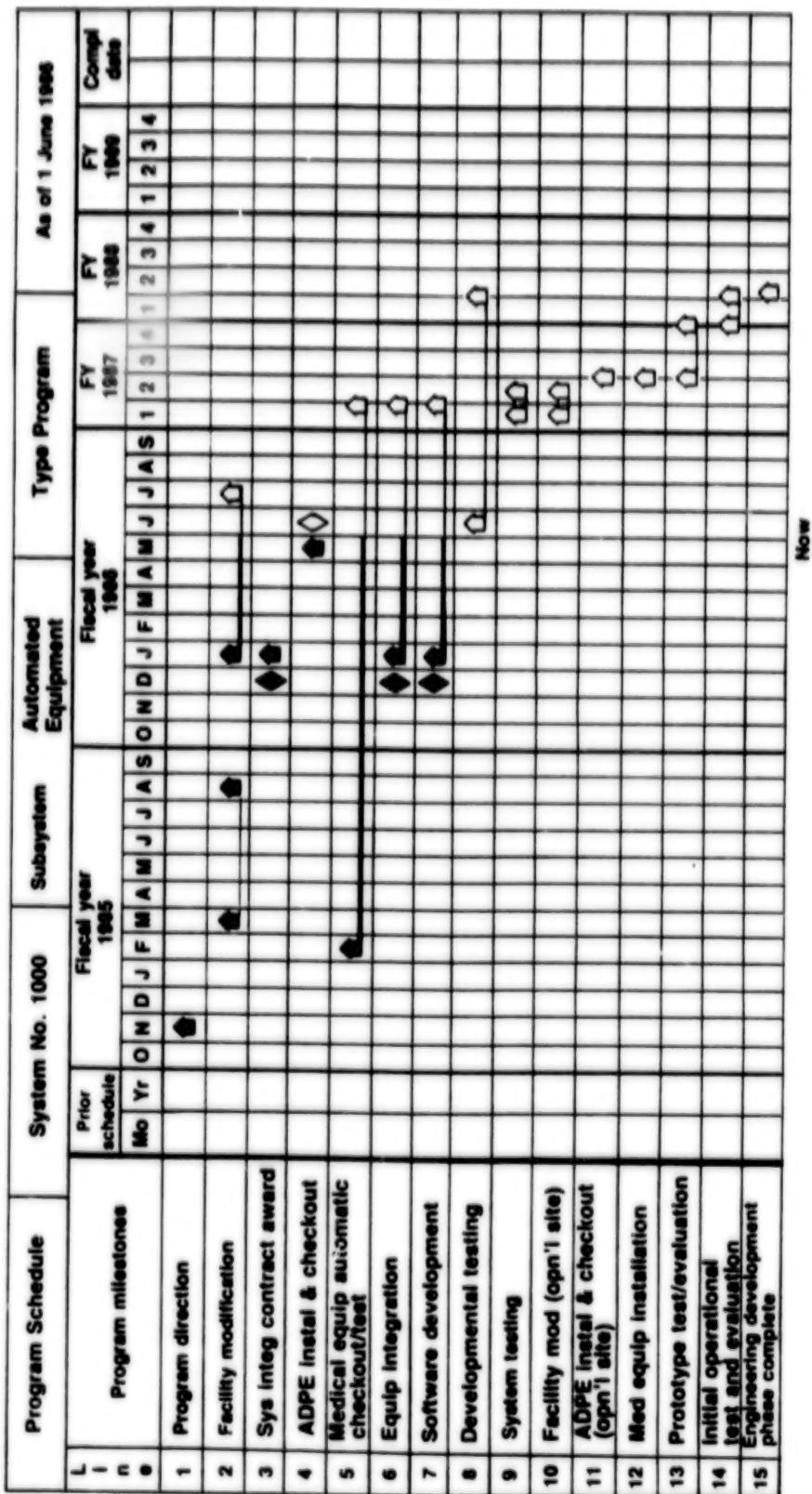


Figure 4. Milestone Chart

Milestone charts represent a simple and effective means to display actual versus planned progress of a program, and to show schedule changes that have occurred. These charts emphasize start and completion dates, rather than the activities that take place between these dates. Milestone charts display very limited dependency information and they may present program status in a deceptively simple manner.

Network Scheduling

Shortcomings of bar and milestone charts gave rise in the 1950s to network scheduling. The network techniques provided a way to graphically display information for program managers that could not be presented with bars or milestones.

First, a program, is separated into activities. Each activity is based on a particular undertaking and each is defined by a distinct start and completion point. Network scheduling provides a method for finding the longest time-consuming path. This gives the manager two important tools. First, the project manager is able to more accurately estimate the total time from program start to completion. Second, by being able to identify items on the critical (or longest) path as opposed to tasks less critical, the project manager is able to analyze problems as they arise.

Program Evaluation and Review Technique

The Program Evaluation and Review Technique (PERT) was developed in 1957 under the sponsorship of the U.S. Navy Special Projects Office. The Navy wanted PERT as a management tool for scheduling and controlling the Polaris missile program, a program which involved 250 prime contractors and more than 9,000 subcontractors. The project manager had to keep track of hundreds of thousands of tasks.

PERT helps answer such questions as:

- When is each segment of the program scheduled to begin and end?
- Considering all of the program segments, which segments must be finished on time to avoid missing the scheduled completion date?
- Can resources be shifted to critical parts of the program (those that must be completed on time) from non-critical parts (those that can be delayed) without affecting the overall scheduled completion date for the program?
- Among the myriad program tasks, where should management efforts be concentrated at any particular time?

Since most activities in a PERT network take a long time to accomplish, time is usually expressed in days or weeks. The expected time for an activity is often described by a probability distribution rather than a single estimate because of the uncertainty associated with programs that have not been done the same way before. The characteristics of the distribution used to express the variation in time are:

- A small probability of reaching the most optimistic time (shortest time), time *a*.
- A small probability of reaching the most pessimistic time (longest time), time *b*.
- The one most likely time which would fall between the two extremes above, time *m*.
- The ability to measure uncertainty in estimating.

Because it has all four attributes, the beta distribution was chosen for determining the expected time. Figure 5 shows a beta distribution with the time designations under the curve.

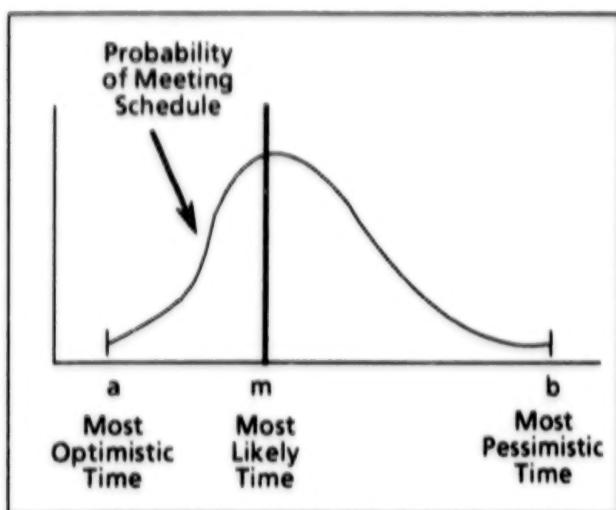


Figure 5. Beta Distribution with Symbols Indicating Time Estimates

The three time estimates shown may be combined into a single workable time value. By using the following weighted average formula, the expected time for an activity can be found:

$$t = \frac{a + 4m + b}{6}$$

where t is the expected time. According to MacCrimmon and Ryavec, the error in the answer using this formula is small enough to make it satisfactory to use in most cases.

According to Hugh McCullough, former Polaris project business manager, PERT had a disciplinary effect. The Polaris project had a 20,000-event network and the application of PERT is credited with saving two years in bringing the Polaris missile submarine to combat readiness.

As PERT's popularity grew, consulting firms specializing in network scheduling sprang up overnight. The DoD established a PERT Operation and Training Center (POTC, nicknamed "Potsie") in Washington, DC. During the next few years, PERT became widely used throughout DoD systems acquisition programs.

A few years later, the use of PERT declined sharply, and by the 1970s, it was rarely em-

ployed in defense systems programs. Why did PERT go through such a rapid rise and abrupt decline? In essence, the predictable happened. When PERT was combined with cost data or other non-scheduling aspects of program management, it became cumbersome. Eventually, use of such an embellished technique resulted in the tail wagging the management dog. The DoD program managers and defense contractors spent immense amounts of time collecting and entering detailed data. Soon, the cost of maintaining PERT systems far outweighed the benefits they offered the program manager.

An article published in the DSMC magazine *Program Manager* reveals how little network scheduling is being used by DoD acquisition program managers. Seventy percent of the major defense programs surveyed do not use a network scheduling system. However, the remaining 30 percent employ a network technique. (Ingalls)

DoD and the defense industry returned to simpler techniques like milestone and bar charts, probably an overreaction. The private sector continues to make good use of network scheduling in varied efforts like new product development, construction, and major maintenance activities. This resurgence is due in part to the development of PERT and other networking software programs that run on microcomputers.

In spite of misuses that have occurred in PERT applications, the technique enables the manager to visualize the entire program, see interrelationships and dependencies, and recognize when delays are acceptable. Thus, the manager is better able to assess problems as the program evolves. In order to apply PERT and similar networking techniques, it is important that certain conditions exist:

1. The program must consist of clearly defined activities, each with identifiable start and completion points.

2. The sequence and interrelationships of activities must be determined.
3. When all individual activities are completed, the program is completed.

Many program-oriented industries, like aerospace, construction and shipbuilding, meet these criteria and use a network scheduling technique. Many defense system programs also meet these criteria.

Critical Path Method

Like PERT, the Critical Path Method (CPM) is composed of three phases: planning, scheduling and controlling. This technique, developed in 1957 by J.E. Kelly of Remington-Rand and M.R. Walker of DuPont to aid in scheduling maintenance shutdowns in chemical processing plants, is essentially activity oriented; PERT is event oriented. CPM has enjoyed more use among network techniques than any other technique.

CPM brings the concept of cost more prominently into the scheduling and control process than PERT does. When time can be estimated closely and when labor and material costs can be calculated early in a program, the CPM technique is superior to PERT. When there is much uncertainty and when control over time outweighs control over costs, PERT is a better technique to use. The basic networking principles in PERT and CPM are similar.

In a common version of CPM, two time and cost estimates are given for each activity in the network. These are the normal estimate and the crash estimate (see Figure 6). The normal time estimate approximates the most likely time estimate in PERT. The normal cost is the cost associated with finishing the program in the normal time. The crash time estimate is the time that will be required to finish an activity if a special effort is made to reduce program time to a minimum. The crash cost is the cost associated with per-

forming the effort rapidly, in order to minimize the time to completion.

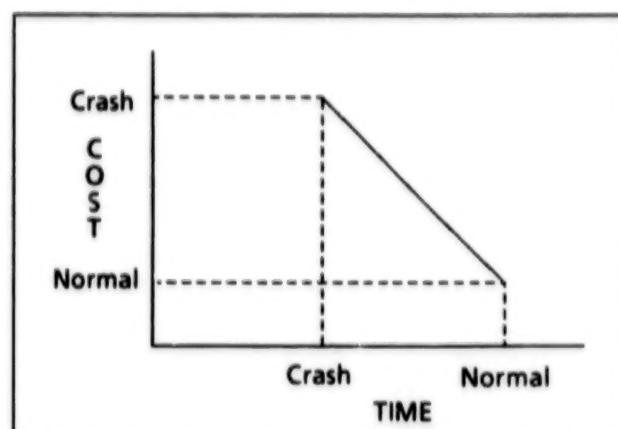


Figure 6. CPM Time-Cost Curve

Developing a Network

Although CPM and PERT are conceptually similar, their symbols and charting techniques vary. The PERT historically has used probability techniques while, CPM generally does not. The following procedure applies to both CPM and PERT.

1. Identify all individual tasks comprising the program.
2. Determine the expected time to complete each activity.
3. Determine precedence and interrelationships of the activities.
4. Develop a network diagram presenting these activities in proper sequence and reflecting any dependency relationships. Activities are indicated by lines; events or milestones are indicated by circles. Dependency or sequencing relationships among activities on separate paths can be shown by dotted lines (dummy activities).
5. Compute and annotate the cumulative time required to reach each milestone along the paths, which will indicate earliest time work can start on the next activity. The final number will indicate the total time required to complete a path.

6. Identify the critical path. This is the sequence of events, or route, taking the longest time to complete.
7. Starting at the program completion milestone on the right side of the diagram, begin working backward and compute the latest time an activity can start without delaying the overall program. For example, if the total program takes 40 weeks and the last activity requires five weeks, the final activity cannot begin later than week 35. The difference between the earliest start time and the latest time before each activity is the slack time, or float. The critical path contains no slack time.

Figure 7 shows a simple network diagram for a computer installation program. This network diagram shows the total program will require 20 days to complete. The critical path

is F-G and any delay on this path will delay final completion of program. However, delay of one day can occur along path C-D-E, a delay of five days can occur along path A-B-E, and the final completion date would not be extended.

Critical path programs may be either activity oriented or event oriented. This means that the input and output data are associated with either activities or events. The distinction between the two is not a substantive one with respect to computational practices.

Although it has not been done in the above example involving the installation of a computer, many CPM programs and a few PERT programs require that events (circles on the diagram) be numbered in ascending order. This inhibits the flexibility of the network and causes event-numbering bookkeeping problems, so it is not always done.

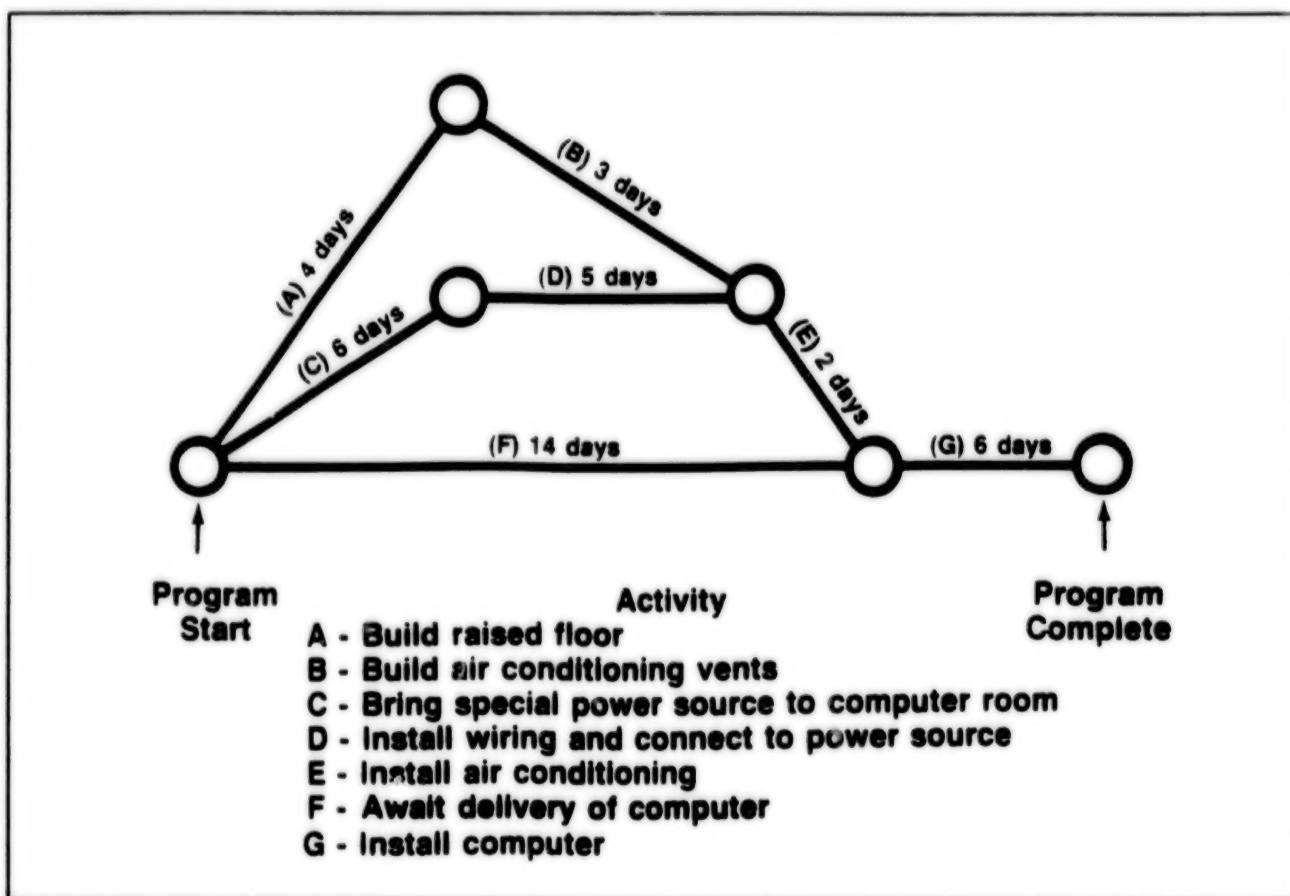


Figure 7. Network Diagram for Computer Installation Program

Converting an Ugly Duckling to a Swan

Although the traditional CPM technique provides useful visibility and clarity about a program, it has shortcomings in that it is difficult to draw the chart to match a time or calendar scale. Although the critical path and slack times can be computed easily, they are not readily apparent. Also, this technique does not display progress to date. Consequently, a simpler technique, sometimes called the Swan Network, is useful.

Let's take an Ugly Duckling Network (Figure 8) and turn it into a Swan Network (Figure 9). Letters in Figure 8 represent activities between the start (S) and completion (C) points. Numbers indicate weeks required for each activity. In Figure 9, activity A is represented by a horizontal bar four weeks long. Constraints are represented by vertical lines or "fences;" for example, the fence after B means B must be completed before E and F can begin (the same as in Figure 8). The result is shown in Figure 9.

What does the Swan network show?

1. The critical path. Time constraints do not have to be calculated. There are, in fact, two critical paths, B-F-I and C-J-K, which are critical because each has a continuous series of activities. There is no slack in either path. Also, the figure has a time scale, which adds greatly to the meaning of the chart.
2. Weeks from start. Scales for "calendar weeks," and "weeks to completion" can be added. In Figure 9, the program is scheduled for completion after 14 weeks.
3. Where there is slack in the schedule and the extent of that slack. For example, there are only two weeks of slack in the A-D-H path. If B-F-I and C-J-K were shortened by more than two weeks, A-D-H would become a critical path. This changing of two critical paths is important when conducting "what if" exercises.

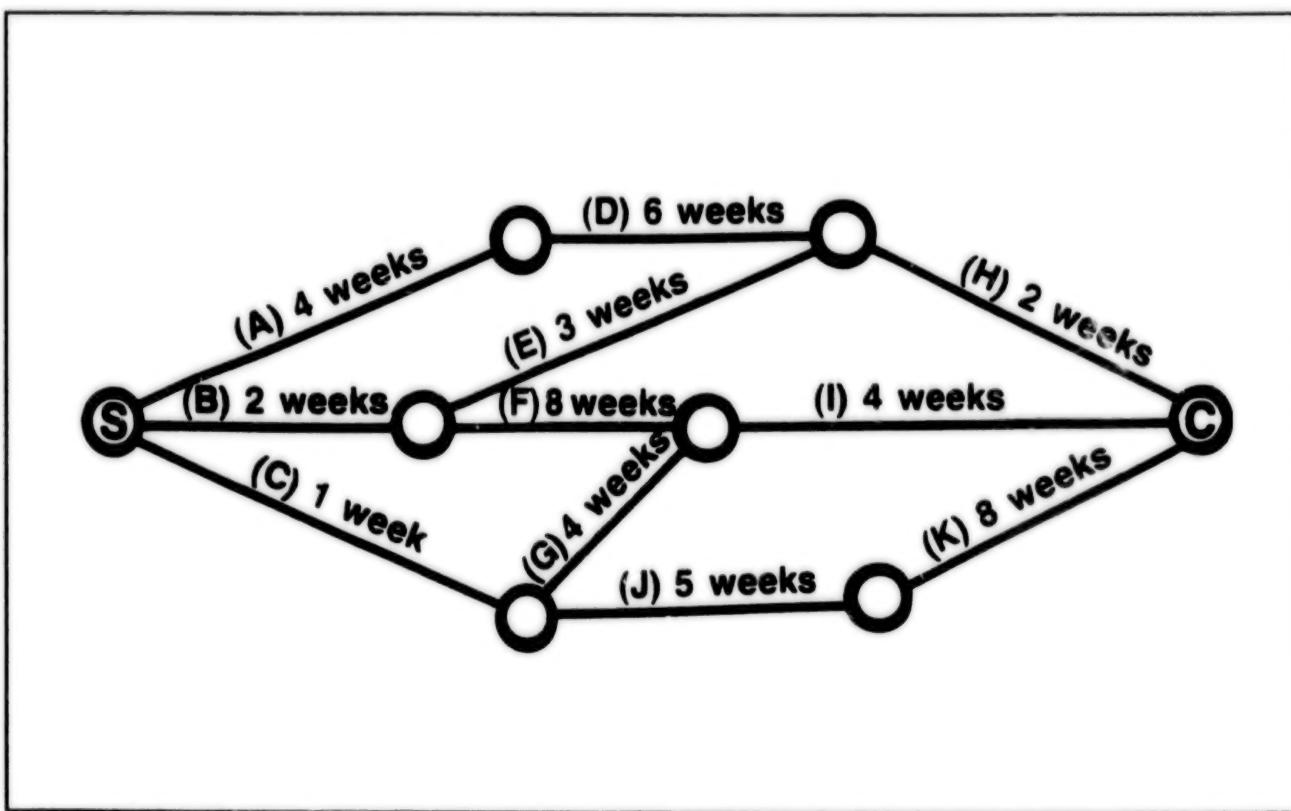


Figure 8. The Ugly Duckling

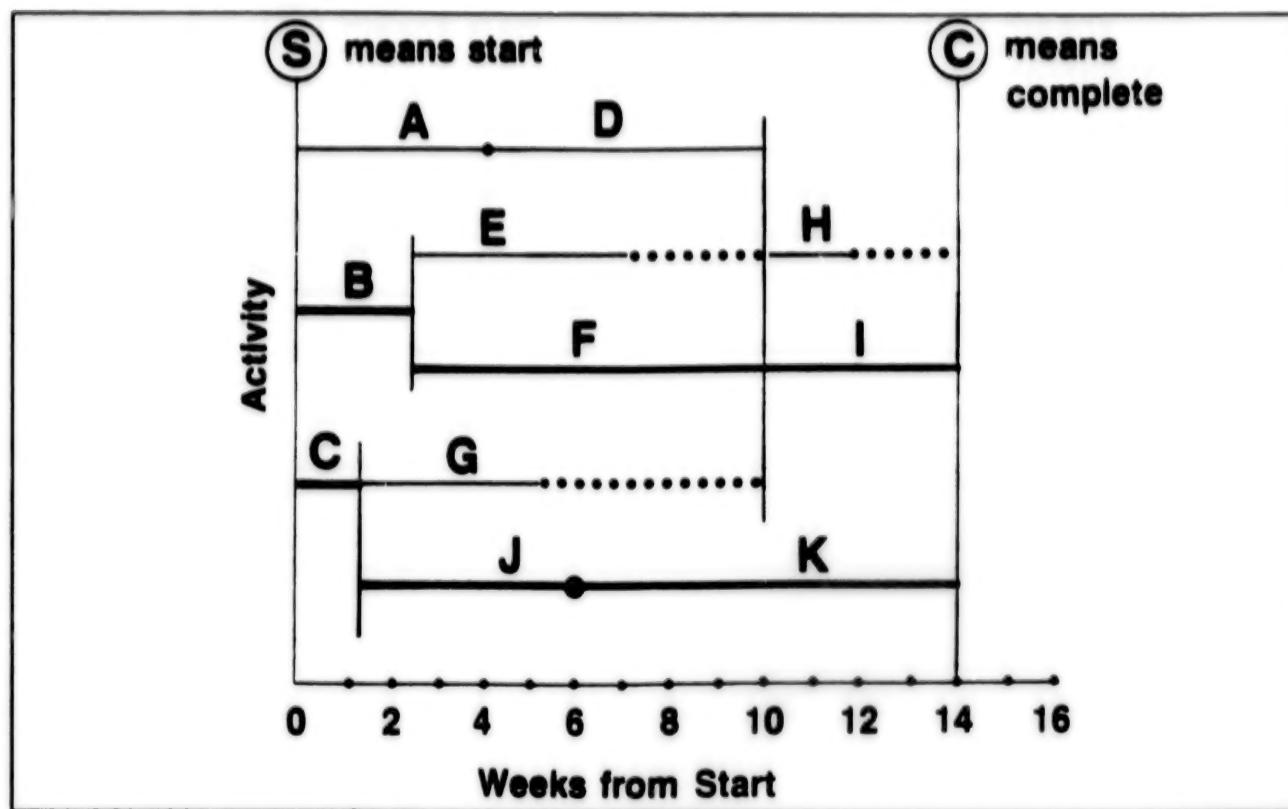


Figure 9. The Swan

The high visibility offered by the Swan network does the following:

- Communicates.
- Motivates. If the level of detail is sufficient, everyone associated with a program activity can see how they affect the schedule, and vice versa.
- Gets top-level attention.
- Makes omissions and errors easier to detect; for example, one company discovered that by using the Swan network, two test activities on the critical path had been omitted. (This was not apparent in the Ugly Duckling network.)
- Shows early start, early finish, late start and late finish.
- Avoids reams of printouts, provided (but not used) for the Ugly Duckling.

The Swan network can be developed in several ways; it can be translated from another network, as shown in the preceding example; it can be developed from a listing of the preceding and following events or activities, as in the network scheduling problem that follows; it can be developed from scratch, with the sequencing and time estimating required in originating any network; and it can be developed from milestones.

A "fence" in the Swan network is usually a milestone like a review or a major event, regardless of how the network is developed.

Actual progress can be shown in the same way as on a Gantt chart. Shading on each bar indicates progress made. A vertical "row" line shows whether activities are on, ahead of, or behind schedule, and by how much.

Now, let's go through an exercise involving network scheduling. Take time to work the problem shown on the following pages.

Network Scheduling Problem

Assume you are program manager. Your objective is to schedule the activities on your program so that one lot of missiles will be assembled and shipped to the test site within 56 days and at the least cost. Use any technique with which you feel comfortable. If you're not comfortable with a particular technique, use the Swan network. Proceed in the following manner, using Tables 2 and 3 provided.

Using lined tablet paper, lay out the normal schedule. This will show the critical path and total number of days required. Identify the initial critical path (number of days). Using Table 3, select the final critical path and related costs that will ensure the completion of the program in 56 days and at the least cost.

It will probably take about 20 minutes for you to determine the solution. The cost for a 56-day program will be in excess of \$778,000.

Table 2. Activities, Dependencies , Times and Costs

ACTIVITY ^a	ACTIVITY DEPENDENCY	TIME (WORK DAYS)	NORMAL COST (\$000)
1-2 Fab. Initial Guidance Assemblies	None	12	60
1-3 Controls Fabrication ^b	None	24	96
1-4 Rocket Motor Fabrication	None	28	105
1-5 Process Warheads (GFE)	None	16	37.5
2-6 Additional Guidance Assemblies	1-2	20	90
2-3 Guidance Checkout and Sub-Assemblies	1-2	16	120
3-5 G&C Sub-Assemblies	1-3, 2-3	8	70
4-5 Machine Rocket Motors	1-4	12	30
5-6 Missile Assembly	3-5, 4-5, 1-5	6	37.5
6-7 Test	2-6, 5-6	10	62.5
7-8 Ship to Test Site	6-7	8	30

Note: a. Table 3 contains "crash" data.

b. Work on controls fabrication cannot start until after day 2 due to limited resources

Table 3. Activity Time/Cost Relationships

Activity 1-2		Activity 1-3		Activity 1-4	
Time	Cost	Time	Cost	Time	Cost
10	62.5	22	105	26	110
		20	117	24	115
		18	127	20	142
Activity 1-5		Activity 2-6		Activity 2-3	
Time	Cost	Time	Cost	Time	Cost
14	60	18	97.5	14	132.5
12	67.5	16	110	12	150
Activity 3-5		Activity 4-5		Activity 5-6	
Time	Cost	Time	Cost	Time	Cost
*	*	10	35	4	60
		8	45		
Activity 6-7		Activity 7-8			
Time	Cost	Time	Cost		
*	*	6	60		

Note: Crash time is in work days and cost is in thousands of dollars.

Crash costs include normal schedule costs. For example, the Activity 1-2 crash cost (\$62.5K) includes the normal schedule cost of \$60K.

The activity marked * cannot be "crashed."

Network Scheduling When Resources Are Limited

In the previous discussion, the assumption was that a new activity could start as soon as preceding activities were completed, because sufficient resources were available to perform the work. In practice, however, resources to proceed are not always available.

Let's look at an example to illustrate how this network differs in format from previous networks. First, it uses curved lines for activities. Second, it identifies each activity in three ways: by a letter (A), (B), (C), etc.; by estimated duration of activity (in weeks); and by number of people available to work on the activity based on the manager's estimate at the time the network is prepared (see Figure 10).

The network in Figure 10 can be shown in another manner (see Figure 11). In this network, each activity is plotted on the schedule graph with a horizontal time scale. The duration of each activity is represented by the length of that activity's line. The description of each activity represents its letter designation and number of people assigned to that activity at the time indicated (size of work group). The row across the bottom shows total people scheduled to work each week. In this example, 5 to 15 people will be needed, depending on the week being scheduled.

Now, let's suppose only nine people are available to work this nine-week period. What alternatives do we have? We can produce a personnel loading chart by plotting the number of people scheduled to work in any week against time (Figure 12). Then, if we know that only nine people are available, we can see we will not have sufficient workers during the first, fourth and fifth weeks. We will have sufficient workers to perform the work scheduled during the second and sixth week.

During the third, seventh, eighth and ninth weeks, we will have a surplus of workers for the work scheduled. The task becomes one of rearranging the schedule so that the peaks and valleys are evened out without scheduling more work than nine people can do. It may not be possible to rearrange the network and still finish the program on time. Under present circumstances, there will not be enough workers to complete the first week's scheduled work on time.

The scheduling problem we are considering can be solved quickly by hand; however, when there are many activities, it becomes very difficult to find the optimum answer, even with a computer. A heuristic program should be used to solve this kind of problem. The heuristic rule is a rule of thumb that works; therefore, collection of rules of thumb is usually known as a heuristic program.

In our example, the heuristic approach is one of finding activities having the most slack and attempting to delay them as long as possible without delaying completion of the entire program. We can delay the start of activity (C) for two weeks and activities (A) and (B) can begin simultaneously without exceeding the limit of nine workers. Continuing to apply this approach, the revised schedule could look like that shown in Figure 13.

When an activity is delayed to improve the schedule, the time which it is delayed is usually shown by a dotted line. At the end of the third week in our example, we had an opportunity to delay activities (D), (G) and (I). We chose to delay (D) and (H) one week and (I) four weeks. Although our example is simple, it is not possible to achieve a perfectly balanced schedule. Given the complexities of the program on which these techniques are often used, most managers would be happy to achieve the success we did in this example.

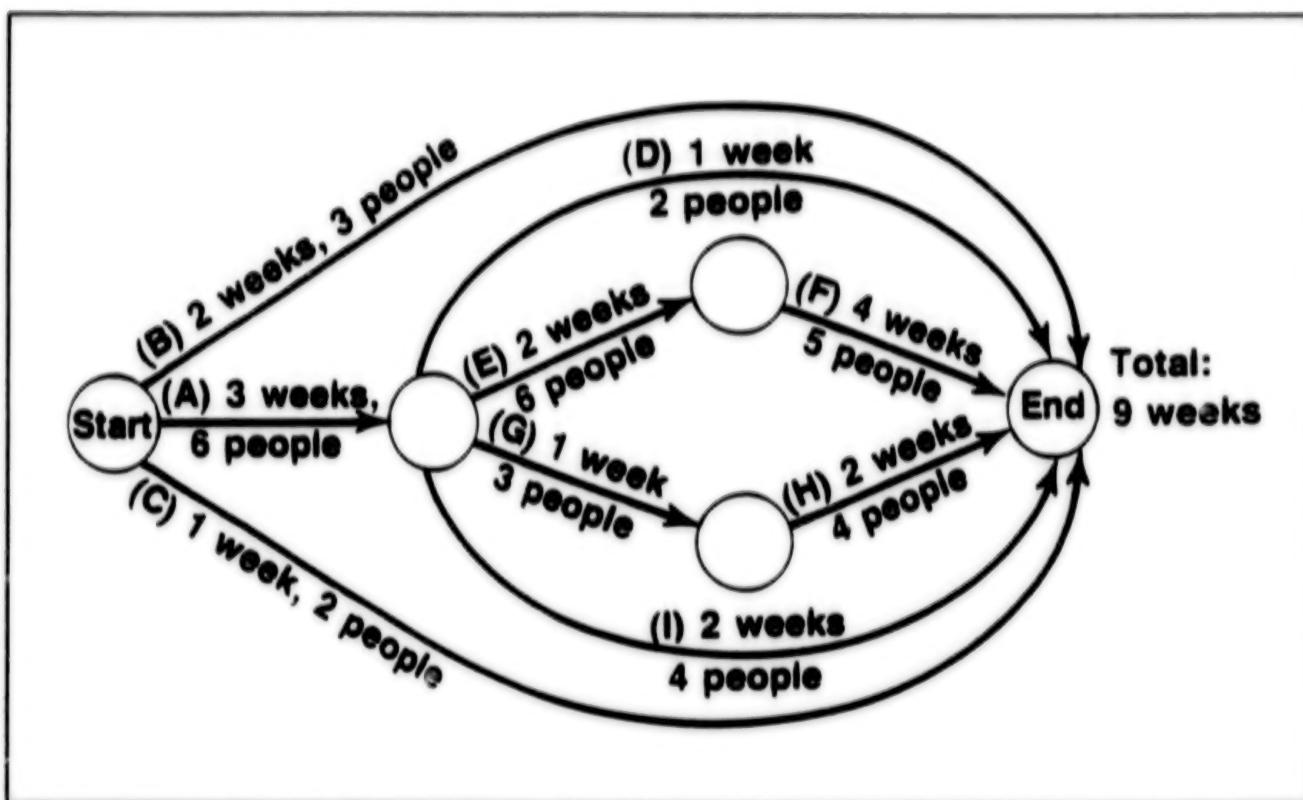


Figure 10. Network Illustrating Problem When Resources Are Limited

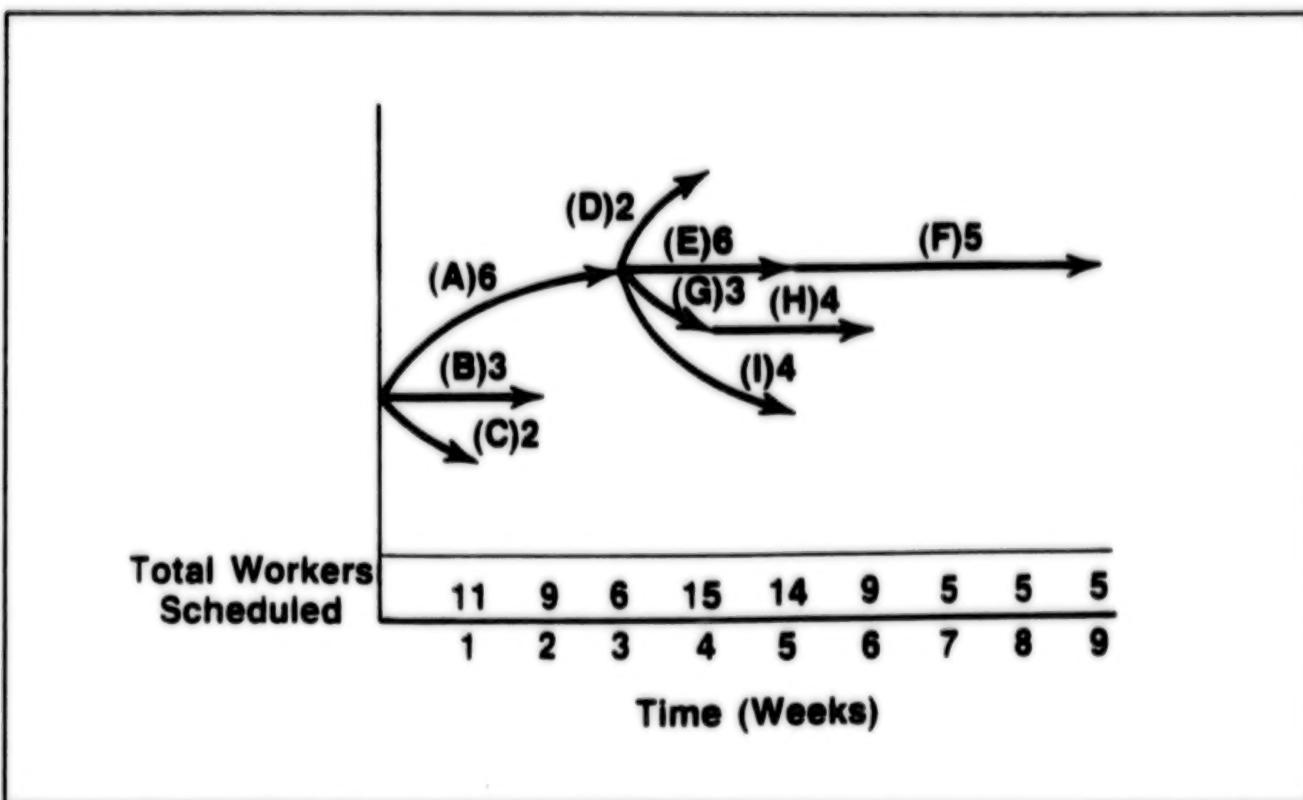


Figure 11. Limited Resource Network Plotted on Schedule Graph

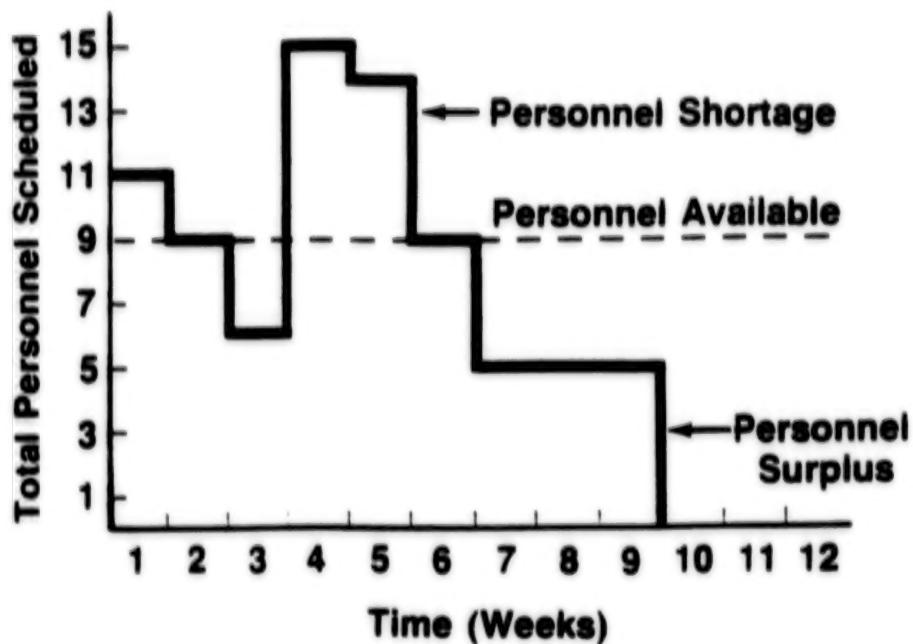


Figure 12. Personnel Loading Chart for Schedule Graph

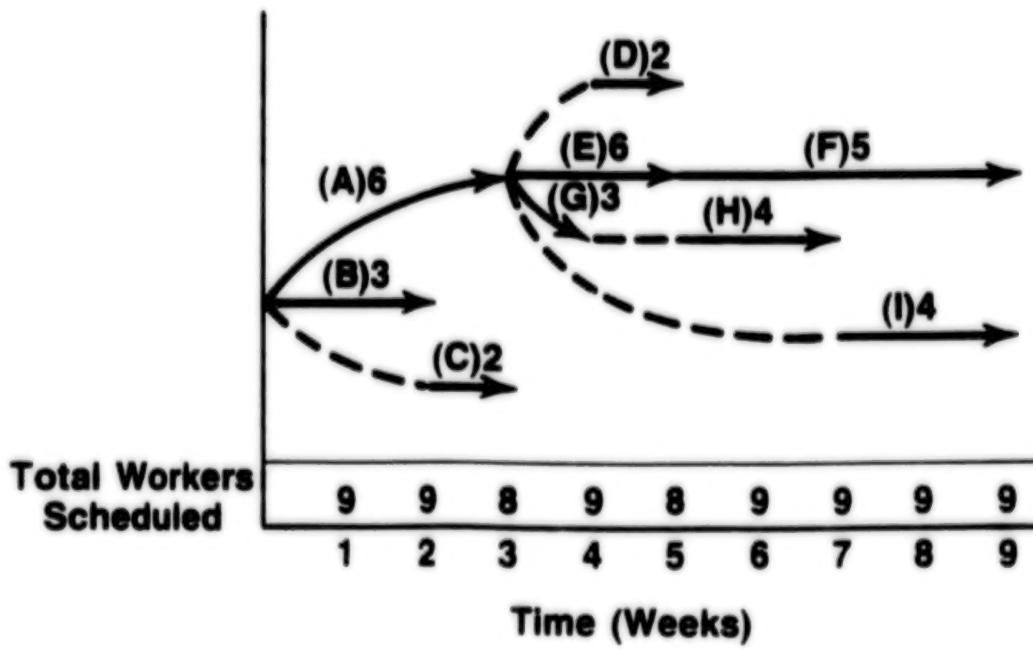


Figure 13. Revised Schedule Graph

Multi-program Considerations

In his dissertation at Purdue University in 1964, J.H. Mize offered a method for multi-method control. He developed a non-iterative heuristic model that schedules activities for several operating facilities of a multi-program organization when the objective is to minimize due date slippage. The outputs from program critical path analyses become the inputs to the schedule. Mize took into account the dynamic relationships of activities to activities and program to program when conflicts arise. The method offered by Mize is applicable generally to any program involving more than one program competing for the same limited resources.

In 1968, L.G. Fendley developed a system based on the concept of assigning the due dates to incoming programs and then sequencing activities of the programs toward meeting the due-date. He used the heuristic approach to solve the scheduling problem. Fendley concluded that giving priority to the

activity with minimum slack-from-due date (his MSF rule) resulted in the best performance. He used the MSF rule to set realistic due dates by determining the amount of slippage that must occur to perform all programs with fixed resources.

In 1970, Mize and L.F. Jordan applied a simulation technique to the scheduling of multi-engineering programs. They discovered that a rule based upon a combination of processing time and due date yielded good results.

All networking concepts can be applied to the scheduling of several programs jointly administered by a single organization. For example, consider the three programs shown in Figure 14. In this example, Program A must be completed before Program B can start. Program C and Program D may begin and be completed any time between week 1 and week 6, respectively. Thus, the dotted lines in Figure 14 indicate dummy dependencies only. They serve to indicate the time span

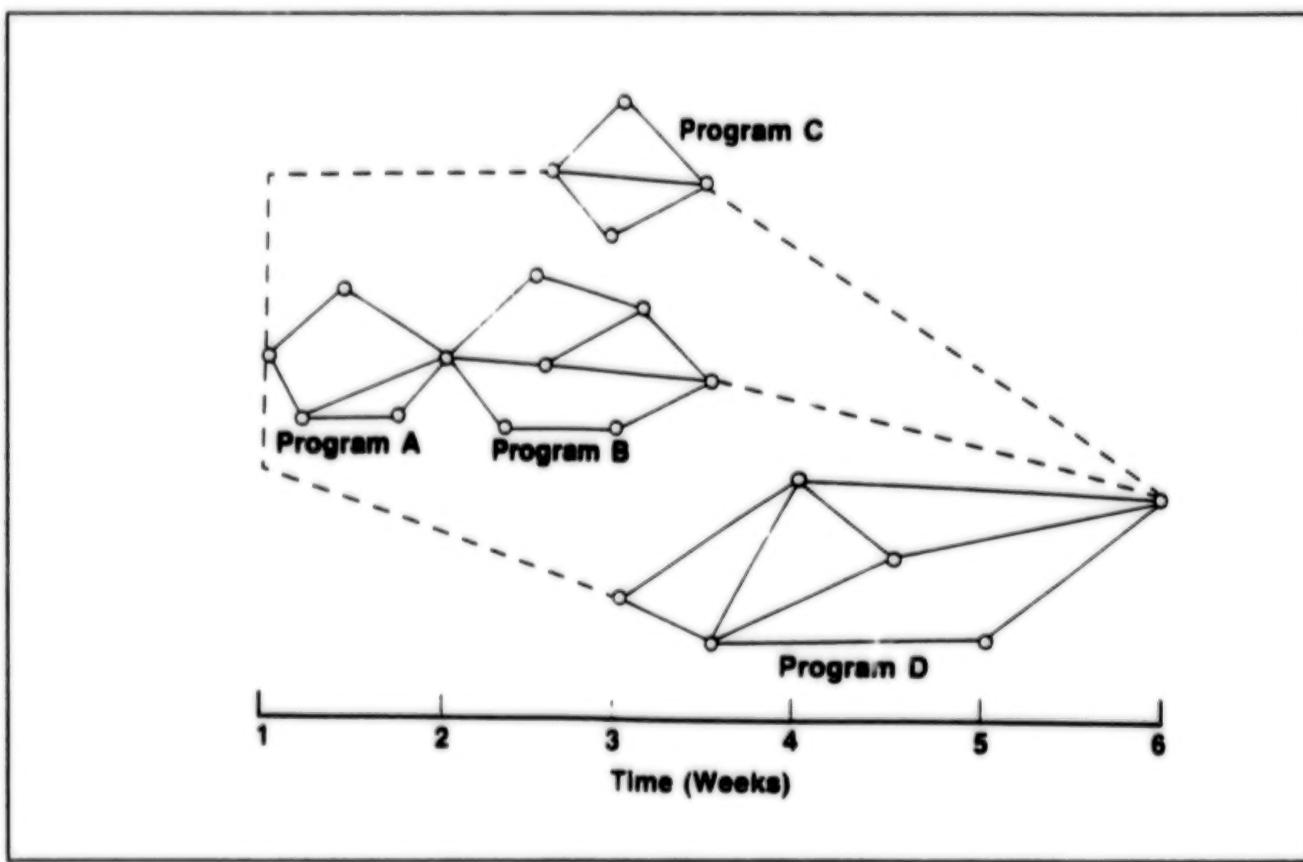


Figure 14. A Multi-program Network

available for all four programs. Duration times could be placed on these dummies to achieve early start and late finish program dates, if they exist. The program floats implied by these dummy jobs can be used in the same way that dummy jobs are used in single-program networks.

For example, suppose the same resources are used on Programs B and C. Furthermore, suppose these resource requirements exceed the availabilities because of the simultaneous demands by Programs B and C. Figure 14 shows that the start of Program C can be delayed until week 4, while the resources are fully employed on Program B. After Program B is completed, the resources can be released for use on Program C. Alternatively, both programs can use the resources at a reduced rate, and both programs will then float out (as long as they do not float beyond week 6.) Whole programs may be cost-expedited. Thus, multi-program networking techniques are completely analogous to single-program networking techniques.

There is, however, one new aspect in multi-program scheduling: program priorities. Suppose that Program C (Figure 14) is deemed to be the most important program and management wishes to have it start before any other program. In the Resource Allocation and Multi-Project Scheduling (RAMPS) computer algorithm developed in 1963 at C-E-I-R, Inc. by Moshman, Johnson and Larsen, the program priority is used as a weighting factor in scheduling and allocating resources among competing alternative uses in the multi-program network.

In general, the iterative use of multi-program level and program-level network methods provides a medium through which program and department level managers may devise integrated total plans. Optimized networks may be submitted by each program manager. In 1974, Woodworth and Dane found these networks could be merged into a

multi-program network. Several multi-program network schedules may be developed, given various assumptions about priorities and resources. These alternative multi-program schedules may then be examined in staff meetings attended by each program manager and multi-program manager. The best multi-program schedule may then be selected, based on discussions and criticisms by everyone involved. Of course, several iterations of the schedule may be required between the program and multi-program level before an acceptable plan is developed.

Influence on Program Performance

Program completion may be strongly influenced by the company's risk-fearing propensity, the customer's decision process and the ability of the company to expand its organization rapidly without losing its effectiveness. On some programs, these aspects may have more influence on performance.

Network scheduling techniques, like PERT and CPM, are much alike in providing interdependencies, depth of detail, a critical path and slack. The swan technique provides simplicity and visibility through time scales that have been used for many years in bar charts.

The choice between PERT and CPM depends primarily on the type of program and managerial objectives. The PERT is particularly appropriate if there is considerable uncertainty in program activity times, and it is important to control the program schedule effectively. On the other hand, CPM is particularly appropriate when activity times can be adjusted readily, and it is important to plan an appropriate tradeoff between program time and cost.

Actually, differences between current versions of PERT and CPM are not necessarily as pronounced as this section may convey. Most versions of PERT now allow only a single (most likely) estimate of each activity time.

When several small programs are to be scheduled, a multi-program network might be considered. In this situation, each program can be treated as a separate entity and the entire set of programs diagrammed and handled as one large network. The RAMPS computer program is convenient to apply in such a situation. The programs in the multi-program network should be importance-weighted or priority-constrained. This will determine which programs to schedule earli-

er than others. Table 4 cites the strengths and weaknesses of network scheduling techniques.

Line-of-Balance Technique

Network scheduling techniques are used primarily in development and other one-time programs. The line-of-balance (LOB) technique is used in repetitive activities like production. In production programs, LOB charts are particularly useful to balance inventory

Table 4. Networking Technique: Strengths and Weaknesses

CRITERIA	STRENGTHS	WEAKNESSES
1. Accuracy	N/A	The technique is as accurate as the activity-time estimates. The margin of error is generally less in construction than in development.
2. Reliability	N/A	Compounded, unreliable estimates in a large program may lead to unreliable status information.
3. Simplicity	Brings simple order out of mass confusion.	Concepts of slack and network families can be difficult to grasp. Computerized networking complicates the process; however, on a complex program without computerization for criteria 5 through 8, the strengths shown cannot be obtained readily.
4. Universality of Program Coverage	Very good for one-time programs like construction and development.	Weak in production phase of life cycle. Not well-suited for quantity production.
5. Decision Analysis	Excellent for stimulating alternatives, especially when coupled with time-cost data.	If computer based.
6. Forecasting	Excellent for forecasting ability to meet schedules.	If computer based.
7. Updating	Easy to update estimates as progress information is received.	If computer based.
8. Flexibility	Portions of network can be changed easily to reflect program changes.	If computer based.
9. Cost		Because considerable data is required, it is usually costly - especially if computerized.

acquisition with the production process and delivery requirements.

A line-of-balance chart shows which control points need attention, not to maintain future delivery schedules. Using the LOB technique, reporting to customers or top management is quick, inexpensive and graphic. Charts used for analysis and trouble shooting are suitable for at-a-glance status reporting. Without a computer controlled production process, the line-of-balance technique doesn't lend itself readily to day-to-day updating. However, a monthly or weekly check usually keeps the process on schedule.

A line-of-balance technique consists of four elements: (1) objectives of the program; (2) production plan; (3) current program status; and (4) a comparison between where the program is and where it's supposed to be, striking the line-of-balance (Figure 15).

The first step in preparing the LOB is drawing the contract delivery schedule on the objective chart (Figure 15-A), which shows cumulative units on the vertical scale and dates of delivery along the horizontal scale. The contract schedule line shows the cumulative units to be delivered over a period of time on the program. Actual deliveries to date (cumulative) are shown. The second step is charting the production plan (Figure 15-B). The assembly plan is a lead time chart. Select only the most meaningful events as control points in developing this chart.

These main events can be given symbols that show whether they involve purchased items, subcontracted parts, or parts and assemblies produced in-house. Assemblies break down into subassemblies, which break down into parts or operations. Thus, one can develop a production plan for any part or level of assembly.

The more steps that are monitored, the more sensitive and more complicated the chart be-

comes. Generally, control points on a single chart should be limited to 50. If there are more than 50, subsidiary production plans can be used to feed the top plan. Thus, each chart can be kept simple and easy to understand. The shipping date of subsidiary charts is when a sub-program must be ready to join the overall schedule.

On the production plan chart, each monitored step is numbered left to right. Step 1 has the longest lead time. The shipping date is the highest numbered step. When two steps are done at the same time, they are numbered from top to bottom.

The production plan chart shows interrelationships and sequence of major steps, and lead times required for each step. An understanding of the manufacturing processes involved and sound judgment are required to know which step and how many steps must be monitored.

The 12 control points in the production plan chart used as an example represent key tasks in manufacturing one lot of missiles. The plan indicates that fabricate ballistics shell (control point 1) must begin 24 work days before government acceptance. Thus, this activity must begin 24 work days before January 1 to meet the first scheduled delivery of five units by the end of December (see the objective chart). The lead time for other control points can be related to the scheduled delivery in a similar manner.

In a five-day-week operation, a month is generally recognized as having 22 work-days. Time for in-house transfer and storage must be allowed in addition to the processing time.

To control production, the manager needs monthly status information for each control point. On the program status chart (Figure 15-C), the bar for control point (12) shows that 14 units of the product have been accepted by the government. The bar for control

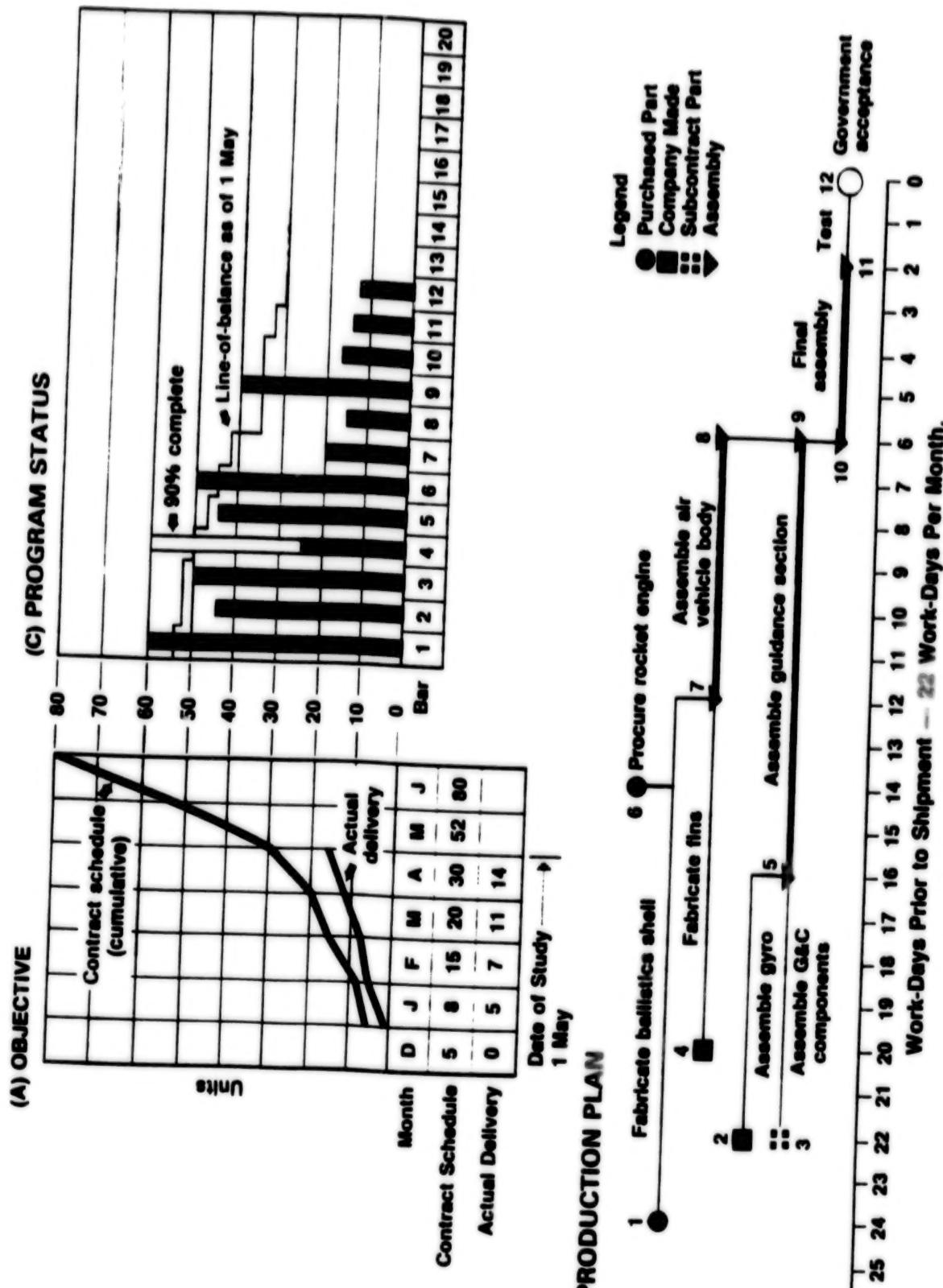


Figure 15. Line-of-Balance Charting

point (9) shows that 40 units of the guidance section have been assembled. The bar for control point (4) shows that in-house fabrication has begun on 60 fins, but only 25 have been completed. The status at other control points are determined in a similar manner. Final deliveries (government acceptances) are shown month-by-month on the objective chart.

To analyze how present status of each control point will affect future schedules, the line-of-balance (LOB) has been constructed. The line-of-balance represents the number of units of the product that should have passed through each control point to satisfy future delivery schedules. This line-of-balance is drawn above the bars on the program status chart to show the status of control points. Normally, the line steps down to the right.

The difference between the line and the top of the bar for each control point is the number of units behind or ahead of schedule. Thus, control point (12) is 16 units behind schedule, control point (9) is 5 units ahead of schedule, and control point (7) is 21 units behind schedule. Control point (12) is behind schedule now, May 1, because there is no lead time available for it. The main impact of control point (7) being behind schedule will be felt in 12 workdays, which is the lead time for control point (7). An insufficient number of assembled air vehicle bodies started into production on May 1. This will adversely affect final deliveries 12 workdays hence. All other control points can be analyzed in the same way.

To recap, the line-of-balance is constructed in the following manner:

- Select a control point, for example (7).
- From the program (Figure 15-B) determine the lead time, the time from the control point to shipment point (12 workdays).

- Using this number, determine the date the units now at the control point should be completed. (May 1 plus 12 workdays is May 16).
- Find the point corresponding to this date (May 16) on the contract schedule line and determine how many units scheduled for completion this represents (41 units).
- Draw a line on the program status chart (Figure 15-C) at that level (41 units) over the control point (7).
- Repeat for each control point and connect the horizontal lines over the control points. The resulting line is the LOB, indicating the quantities of units that should have passed through each control point on the date of the study (May 1) if the delivery schedule had been met.

Analysis

Using the LOB charts in Figure 15, management can tell at glance how actual progress compares with planned progress. Analysis of charts can pinpoint problem areas. Delays at control point (7) in the example may have been causing final delivery problems throughout the contract. However, the purpose of line-of-balance analysis is not to show what caused the slippage in the shipping date, but to detect potential future problems.

In the example, the government acceptance point is control point (12). The bar does not reach the line-of-balance; therefore, deliveries are behind schedule. Control points (10) and (11) are short. However, point (9) is on schedule. Since point (10) depends on points (8) and (9), we know control point (8) is the offender. Both points (7) and (8) are short, but there are more than enough purchased items at control point (6). What's the problem with control point (7)? Trace it back to control point (4), which is seriously short. It is obvious that not having enough completed-fins is holding up the whole progress. Control

points (2), (3) and (5) are short, but are not directly responsible for the failure to meet the delivery schedule. The problem with the fins should be addressed before management attention is devoted to other short operations. The averages at control points (1) and (6) may be examined from the point of view of inventory control.

Updating the charts requires a good status reporting system, which can be mechanized if the program is large and complex. A computer program, developed by the U.S. Army Management Engineering Training Activity (AMETA), Rock Island, Illinois, provides printouts of all information required on LOB charts. Actually, because the program provides all information, printouts can be used by themselves. Charts are not required, but a graphic display of the information is usually desirable.

The line-of-balance is a means for measuring actual progress against a scheduled objective. It employs the exception principle. The four phases to line-of-balance are: the objective, the program, program progress and comparison of program progress to the objective. The statement of objective is presented in terms of the number of units/time period,

number of units to be delivered, scheduled completion date or any other appropriate quantity/time combination (Figure 15-A).

The graphical representation of the principal steps to be taken enroute to the objective—a modified Gantt Chart—is shown in the production plan chart (Figure 15-B).

The graphical representation of the inventory of the stock status for the principal steps is shown in the program status chart (Figure 15-C) with a vertical axis of the same units as those shown in the objective chart.

Striking the line-of-balance involves transferring points from the objective chart to the program status chart for the date being studied. A program that is exactly in phase results in a line-of-balance that intersects every bar of the program status chart at (or near) its top.

Because the LOB technique is production oriented, it provides quick detection of bottlenecks in the production process. Management can then take appropriate action, such as increasing resources at each bottleneck. Table 5 summarizes strengths and weaknesses of the LOB technique.

Table 5. Line-of-Balance Technique: Strengths and Weaknesses (In Production)

CRITERIA	STRENGTHS	WEAKNESSES
1. Accuracy	Completion time estimates are good because work is repetitive; however, this may not be true early in the production phase of a program.*	N/A
2. Reliability	Compares favorably with Gantt technique.	N/A
3. Simplicity	N/A	Construction of the line of balance is not always understood.
4. Universality of Program Coverage	N/A	Well suited only for production phase of life cycle. Does not emphasize resource allocation directly.
5. Decision Analysis	N/A	No capability to simulate alternatives.
6. Forecasting	Very good for indicating whether or not schedules can be met.	N/A
7. Updating	N/A	Considerable clerical effort is needed to update graphs. Computer processing can reduce this effort.
8. Flexibility	N/A	Inflexible. When major program changes occur, all LOB phases must be redesigned.
9. Cost	Data gathering and computations can be handled routinely and at moderate expense.	

* Most of the production span time (~70 to ~80 percent) consists of wait and move time. These times are usually less accurate than the standard times used for set up and run. Reporting accuracy is a key to the reliability of this technique.

"Dost thou love life, then do not squander time for that's the stuff life is made of."

— Benjamin Franklin

Time Management

Program managers are busy people, particularly those in the DoD and defense-related industry. Therefore, it is important that program managers manage time well. Some managers could be more productive, perhaps as much as 20 to 40 percent, by applying effective approaches.

This section concerns the aspects of time management related to programs: the program manager's time reserve, a "now" schedule and value of time.

In contractor performance measurement, much emphasis is placed on "management reserve," the reserve budget controlled by the industry program manager. The program manager doesn't know when or where this reserve will be needed. But the program manager in industry and his counterpart in DoD know it will be needed.

A time reserve is needed as well as a budget reserve; the program manager needs a time reserve to accommodate unknowns that he will encounter. The use of time reserve should be approached with caution, especially where it is visible, so as not to negate the value of the schedule plan and status for management use.

Literature describing a program manager's time reserve is scarce. Based on discussions with a sampling of managers of large and small programs, the main aspects of time reserve are clear.

- Most program managers establish a time reserve of about 10 percent. On a 40-month program, for example, a four-month time reserve would be established.
- The time reserve must be held closely by the program manager, otherwise every manager on his program may think, "I know there's a time reserve; I don't really have to meet my schedule." The program

manager may place this reserve under "additional system tests" or another downstream activity. The point is, it shouldn't be visible. (A built-in safety factor between the manufacturing schedule and the delivery schedule is often used.)

- A tough and disciplined approach to meeting the published schedule is required from the start of a program in order to maintain the reserve and, consequently, to meet the program schedule in spite of slippages caused by the unknown unknowns (unk unks) that inevitably arise.

A direct relationship exists between time and cost for any activity. This relationship takes into account the people, resources and method used, and considers the efficiency achieved. Generally, the least costly schedule is the current one. To speed up the schedule costs more; to stretch out the schedule also costs more. The sum of the direct and indirect costs gives a U-shaped total program cost curve. The optimum schedule for implementing the program is the schedule corresponding to the minimum point on this curve. The relationship among direct, indirect and total program costs is shown in Figure 16.

Because schedule stability affects program costs, which may, in turn, affect technical performance, it is clear that schedule stability has a great deal to do with whether the program meets its cost and technical objectives. Unfortunately, budget constraints and other factors, like changes in quantities (items over which the program manager has no control) have often been imposed on a program with the comment, "Do the best you can."

When a schedule must be revised, the superseded schedule is often discarded. If the new schedule is superseded, the process is repeated. Often, the organization causing a slip in

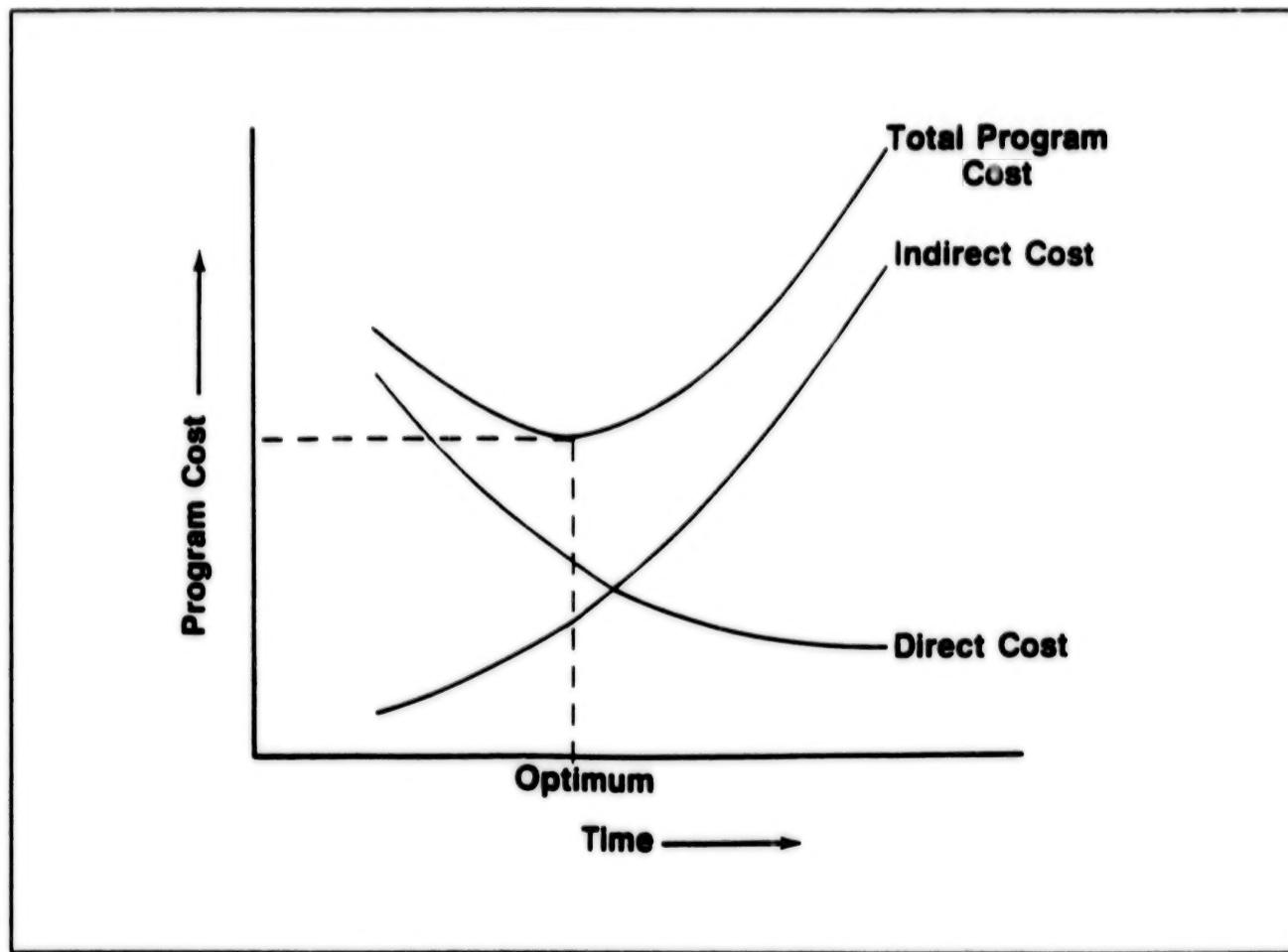


Figure 16. Total Cost Analysis for Selecting "Optimum" Program Duration

schedule becomes a repeat offender. The principal value of retaining a former schedule is in being able to identify the offender, thus making schedule slips less acceptable.

The significance of maintaining a stable schedule is becoming more widely recognized. Appendix A describes the development of a master schedule and the importance of maintaining schedule discipline.

While serving as under secretary of defense (research and engineering), Dr. William J. Perry said, "Our acquisition process is cautious, slow, and expensive. It now takes us 12 years or more for development, production and deployment of a typical (defense) system, so that our lead in technology is lost by the time the system is deployed."

According to the late John H. Richardson, president of Hughes Aircraft Company, "A basic reason for adopting project (or program) management, when tackling the difficult and unique tasks associated with developing and producing a system, is to eliminate unnecessary delays in accomplishing the job at hand. Time is a resource in systems management, to be treated with indifference or used well like any other resource. For projects not yet in full swing, it is important to recognize that time has economic value, and that we may be taking time too much for granted." Richardson cites historic reasons for stretching out program schedules.

- Funding can create a problem. In hungry years the schedule is often stretched because of reduced funding.

- A better product can be expected if it is more thoroughly debugged and tested. However, a system does not really get wrung-out until it is in the user's hands, regardless of beforehand debugging.
- Cost of concurrency (overlap of development and production), may lead to a decision not to overlap program phases. Such a decision may be popular in many cases but it cannot be tolerated when the pendulum swings toward the importance of time; that is, when top management says "Get the system out the door; never mind what it costs."

Stretched-out schedules incur cost penalties because of inflation, additional engineering changes, and changes in program managers or other key program management officials. Another near-term cost results from the increased chance that a program will be canceled because of obsolescence or competing technology. History shows that stretch-outs invite cancellation. Also, competing technology, which may get a toe-hold during a program stretch out, may lead to a program cancellation. Long schedules with no opportunities to incorporate improvements are a negative factor when considering a new start.

Delayed decisions increase costs. For example, waiting to acquire 90 percent of the facts bearing on a decision, rather than going ahead when 80 percent of the facts are in hand, is not usually cost effective. The schedule is prolonged when the decision is withheld.

According to R. W. Peterson, former Du Pont executive, "All business men are concerned, and properly so, about the long time it takes to move a new development from its inception to a profit status. But frequently forgotten is the fact that a month's delay in the early stages of development is exactly as long as a month's delay in the later stages. While it may seem innocuous to put off a decision for

a month or two in the early years of the project (or program) with an uncertain future, that delay may turn out to be just as costly as is procrastination when the final decisions are made. In short, a sense of urgency is essential to decision making in all stages of a new venture, not just the latter stages."

A consideration having more impact on the value of a defense system, a point often overlooked, is the useful life of the system. Leading producers of commercial and industrial products are aware of the importance of bringing a new product to market without delay to gain the greatest return on the costs of product development and production.

Making use of time to increase the life of a system applies to defense systems as well as to commercial/industrial products/systems. Concentration on system or product cost, without considering the life of the resulting system or product, overlooks a key point: whether the buyer obtains value for each dollar. The most costly product, in terms of value, is one appearing when it no longer fulfills a useful purpose, even though it has been produced at minimum cost. Each month added to the development and production of a new high-technology system or product tends to reduce by one month the operational life of the system or product.

In spite of the 10 to 20 percent cost premium that may be paid for tight scheduling, as compared to orderly but stretched-out scheduling, the longer resulting operational life usually provides greater economic value. This is looking at time only from the viewpoint of economics; i.e., acquisition cost per year of operational availability.

Another way of looking at time is that defense system availability is survival insurance. An executive of a major shipbuilding company noted that, "the time we're spending waiting for our ships to come in . . . is time we just may not have."

Consideration of alternative plans and schedules will also help; e.g., if event so-and-so occurs, proceed with plan "A"; if event such-and-such occurs, proceed with plan "B", and so on. Anticipation and preparation for most likely events, along with the tools described, and coupled with effective communication of the plans, can change the management style from crisis management to skillful management.

Planning and scheduling can do much to prevent running out of time and having to make the least desirable decision because of lack of time. Establishing a time reserve, a "now" schedule and recognizing the value of time in decision making all contribute to the manager's repertoire of good tools.

Sir Jeffrey Quill, manager of the British Spitfire Development Program, commented during a visit to the Defense Systems Management College that, "After 1935, costs were not particularly important. What mattered was time. We worked three shifts a day. Everything was time. Quantity and time. It turned out that we probably produced at the lowest cost too; but the emphasis was on time."

"I wasted time: now doth time waste me."

- Richard II

Recapitulation

The program manager is responsible to top management for getting the job done on schedule and within the allowable cost. Today, network based systems assist the manager in planning, scheduling and controlling the work to be accomplished—often by people in separate organizations not under the manager's direct control. The manager needs a plan that will provide a constant and up-to-date picture of the operation that is understood by all.

Scheduling, cost and performance are major elements of concern to the program manager,

who should be able to blend them to meet program objectives. When selecting a scheduling method, the program manager can make a conscious tradeoff between the sophisticated methods available and cost.

Gantt charts can be used effectively for small programs and when program activities are not highly interconnected. Often, a Gantt chart is selected because, considering the benefits it will provide, network scheduling does not justify the additional cost. Figure 17 illustrates the evolution of network-based systems. The differences between the CPM and PERT techniques result from the environments in which they evolved.

The CPM arrow-diagram network evolved from activity-oriented bar charts. The arrow diagram resulted from linking the activities in a sequence of dependence, often without identification of the connecting points. Factors leading to the CPM technique are a well-defined program, a dominating organization, few small uncertainties and a single geographical location for the program.

The PERT network evolved from a combination of bar charts and milestone charts on which the milestones were identified as events, or specific points in time. The PERT network is heavily event-oriented. Factors that led to the development of the PERT technique are large programs with difficult-to-define objectives, multiple and overlapping responsibilities among organizations, large time and cash uncertainties, and wide geographic dispersal of activities and complex logistics.

When network scheduling is justified, and you wish to choose one of the methods discussed in this guide, be sure to consider that many network scheduling methods are computerized. Software packages are available commercially, or at DSMC, to cover many scheduling methods.

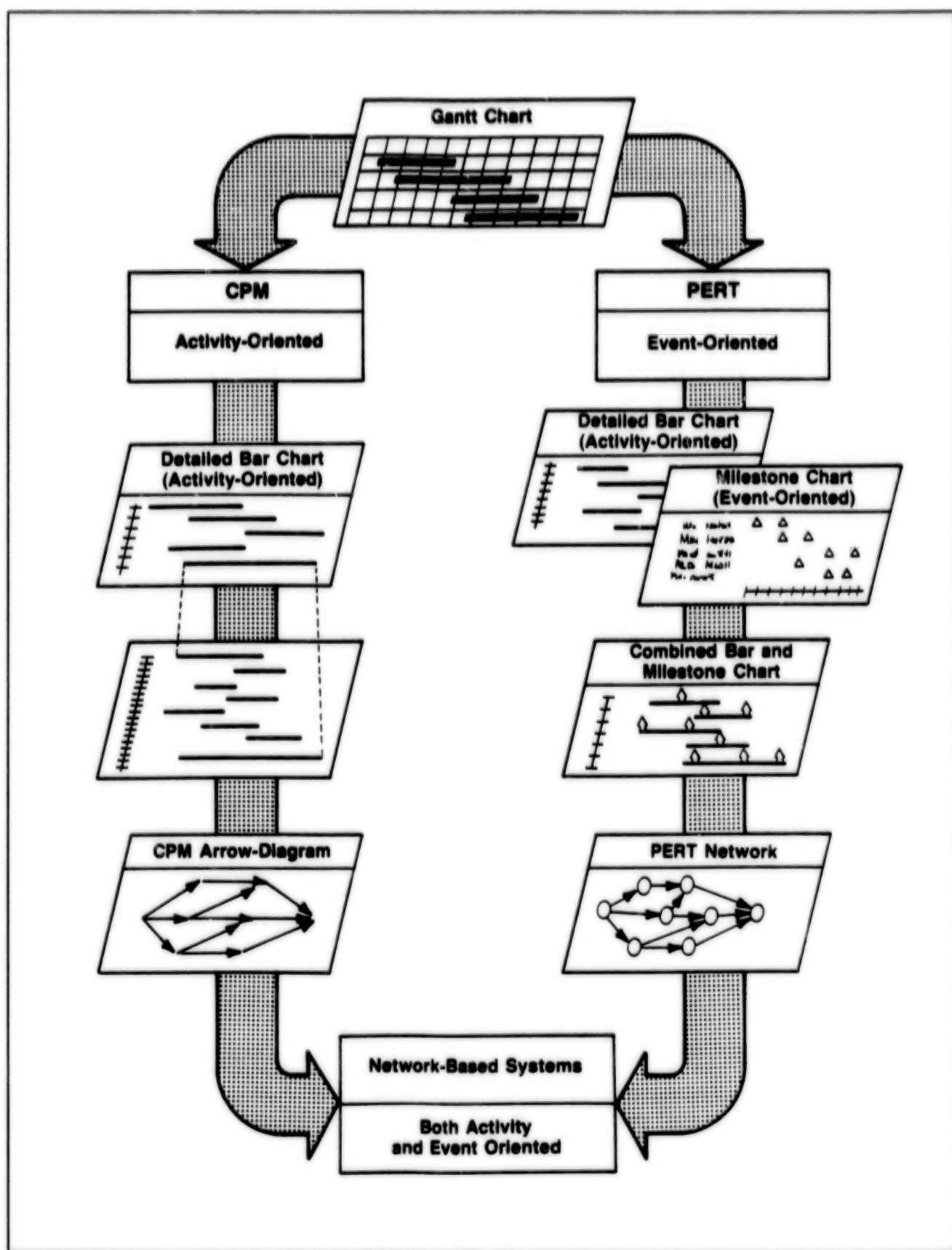


Figure 17. Evolution of Network Based Systems

The principal points to be derived from this section include the following:

- Schedule, time and cost are three major elements to control in any program. These can be in conflict and, tradeoffs may have to be made.
- All programs involve planning, scheduling and controlling. During the planning phase, objectives, organization and resources are determined. During the scheduling phase—the phase with which this section is concerned—personnel requirements have to be determined; time to complete the work and the cost have to be estimated. During the control phase, the program's progress in terms of time, cost, and performance have to be measured. Necessary corrections have to be made to ensure achievement of the program objectives.
- The activity oriented Gantt charts are useful when activities are not closely related and the program is relatively small. The chart shows relationships among variables clearly and quickly, and focuses on situations needing attention.
- The milestone charts, which are event-oriented and display start and completion dates, invite surprises because the program manager may not know the status until an event occurs or fails to occur.
- The network displays how a program can be done and the schedule establishes how it is planned to be done.
- A network identifies the critical path, slack (time an activity or event can be ex-

tended and still be completed on time) and activities needing rescheduling. Activities on the critical path have zero slack and must be completed on time to prevent slippage of program completion date.

- The PERT network-based scheduling method may use three time estimates for each event: most optimistic time, most pessimistic time and most likely time.
- The CPM, a network-based scheduling method, uses a linear time-cost tradeoff; i.e., it adds the concept of cost to the PERT format. If necessary, each activity can be completed in less than normal time by crashing the activity for a given cost.
- The line-of-balance (LOB) technique of scheduling is effective in manufacturing where a final assembly line is fed by many component lines, and delivery of end-units is required at predetermined specified intervals. The effectiveness of LOB is based on the design of the assembly plan.
- Computer programs are available for network-based scheduling. Manual calculations are feasible for small problems like those set forth in this section; however, computer assistance is usually necessary for large, complex problems.
- Network theory assumptions that activities are independent, discrete and predictable are not always appropriate in actual applications. The departure from reality, however, does not normally affect planning and coordinating efforts on critical-path scheduling.

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AN ANALYSIS OF COST OVERRUNS ON DEFENSE ACQUISITION CONTRACTS

by David S. Christensen

Donald J. Yockey, the former Under Secretary of Defense for Acquisition, has called for more realism in the defense acquisition process. More specifically, he has called for realistic cost estimates. The hope is that more realistic estimates will help surface problems in enough time to resolve them.

Based on a review of over 500 contracts, the Office of the Under Secretary of Defense for Acquisition has observed that once a contract is 15 percent complete it is highly unlikely to recover from a cost overrun. Despite this important observation, contractor and government personnel often claim that their programs are different.

This article examines the history of cost overruns reported on 64 completed defense contracts. Its purpose is to formally test the observation of the Under Secretary. Results confirm the observation at the 95 percent level of confidence, and were generally insensitive to the contract type (price, cost), the contract phase (development, production), the type of weapon system (air, ground, sea), and the armed forces service (Air Force, Army, Navy) that managed the contract. After a review of terminology, concepts and related research for those unfamiliar with the area, the methodology, results and managerial implications are described.

Background

Jacques Gansler reports that the average cost overrun on defense acquisition contracts is 40 percent. Cost data on defense contracts are regularly reported on cost management reports prepared by defense contractors. These reports include the Cost Performance Report (CPR) and the Cost/Schedule Status Report. Department of Defense Instruction 5000.2 requires the CPR on all contracts judged significant enough for Cost/Schedule

Control Systems Criteria (C/SCSC). Significant contracts are research, evaluation, test and development contracts with estimated costs of \$60 million or more, or procurement contracts with estimated costs of \$250 million or more. Thus, a 40 percent cost overrun on a procurement contract that barely qualifies as significant is at least \$100 million dollars!

The cost/schedule control systems criteria are not a system. Instead, they are minimal standards for contractors' internal management control systems. The purpose of the criteria is to foster reliable decision-making by contractor and government personnel. One of the requirements is that data reported by the contractor be summarized from the same systems that the contractors use for internal management. These and other requirements help ensure that the data submitted to the government is useful for decision making.

Another requirement of the criteria is a disciplined budgeting system. A time-phased budget of all the authorized work on the contract, termed the "Performance Measurement Baseline," is developed by the contractor. The baseline is simply the summation of budgets assigned to elements of work on the contract. Because each element of work has a schedule, the budget for the work is said to be "time-phased."

The time-phased budgets assigned to work elements, termed the "Budgeted Cost of Work Scheduled" (BCWS), form the basis for earned value measurement and reporting. Earned value, also termed the "Budget Cost of Work Performed" (BCWP), is the same number as BCWS. The only difference is when they are recorded. BCWS is recorded when work is planned to be accomplished, and BCWP is recorded when work is actually

accomplished. If work is accomplished at a time different than it is planned to be accomplished, then a schedule variance is identified. In a disciplined budgeting system, all significant variances are investigated in a timely manner.

A schedule variance often signals a cost variance. A cost variance is simply the difference between the budgeted cost of work performed (BCWP) and the actual cost of work performed (ACWP). As with the schedule variance, the criteria require the timely investigation and reporting of significant cost variances. The intent is that through the timely analysis of variances, problems will be corrected before they become serious.

Figures 1 and 2 illustrate the relationship between the three basic data elements just described. The performance measurement baseline is the cumulative expression of BCWS. Against this baseline, performance (BCWP) and actual cost (ACWP) are measured. Figure 1 illustrates the typical condition of defense contracts: over budget and behind schedule.

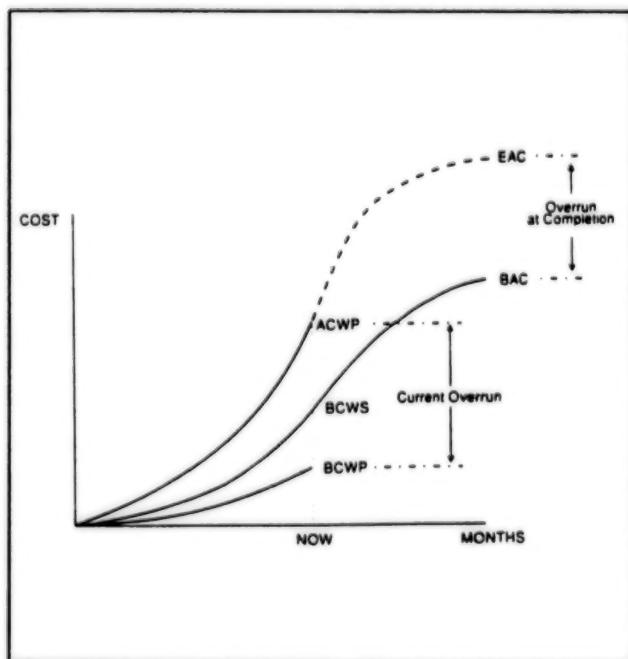


Figure 1. The Current Cost Overrun and Overrun at Completion

A cost overrun is an adverse cost variance. Figure 1 illustrates two kinds of cost overruns, termed the "current overrun" and the "overrun at completion." The current overrun is the adverse cost variance to date. The overrun at completion is the difference between the total budget for all the work on the contract, termed the "Budget At Completion" (BAC) and the estimated final cost of the contract, termed the "Estimate At Completion" (EAC). Note that the overrun at completion is an estimate until the contract is completed. As shown in Figure 2, at the end of the contract, BCWP equals BCWS and the current overrun is the final overrun.

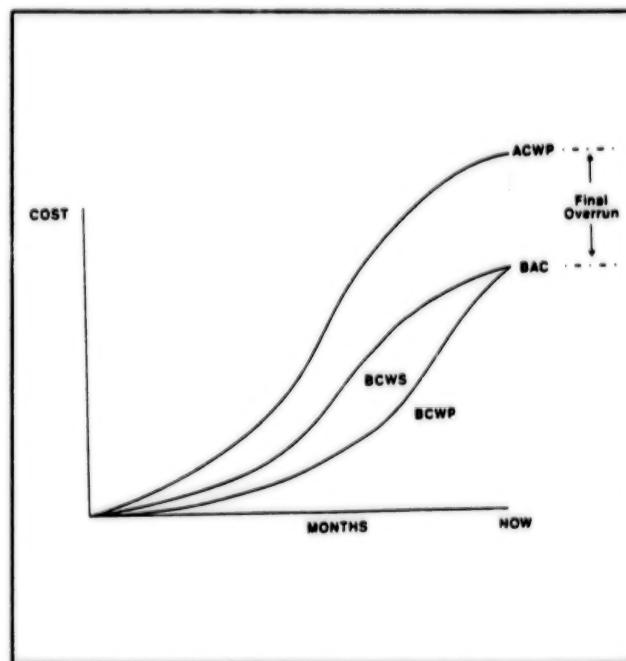


Figure 2. The Final Cost Overrun

The estimate at completion is an important number and is very controversial, largely because there is literally an infinite number of possible EAC formulas. The criteria do not prescribe a particular formula or set of formulas; the choice is the contractor's. The only requirement is that the estimate be rational.

Because rational people can disagree, the government will usually evaluate the reasonableness of the contractor's estimate by computing a range of EACs. Unfortunately,

there is little guidance on what constitutes a reasonable range. As a result, the projected overrun at completion supported by the government program office is usually higher than the contractor's estimate. Because the government program office is necessarily an advocate of their program, their estimate may also be unrealistically optimistic.

One way to assess the reasonableness of the estimated overrun at completion is to compare it to the overrun to date. If the overrun at completion is less than the overrun to date, then the contractor or program office is optimistically projecting a cost recovery. Such was the case in the A-12 program. In April of 1990 the A-12 was in full-scale development and was 37 percent complete. The contractors' reported overrun at completion was \$354 million. The overrun to date was \$459 million. Thus, the A-12 contractors were predicting a recovery of \$105 million. Although this may seem optimistic, it is impossible to know for sure because the A-12 was canceled in January of 1991.

Is such optimism justified? More specifically, is it unrealistically optimistic for the predicted overrun at completion to be less than the overrun to date? Based on a review of cost overrun data on completed contracts, the answer is that such optimism is unrealistic with 95 percent confidence.

What Prior Research Says

There has been some research into this issue. Wayne Abba and Gary L. Christle, senior analysts at the Office of the Under Secretary of Defense for Acquisition, have observed:

Given a contract is more than 15 percent complete, the [final] overrun at completion will not be less than the overrun to date, and the [final] percent overrun at completion will be greater than the percent overrun to date.

This observation is based on a review of cost data on over 500 completed contracts. The analysts are quick to point out, however, that timely management attention to adverse cost variances can reverse them, especially early in the program. The problem has been a failure to use performance measurement data proactively.

The assertion of Abba and Christle is based on a casual review of over 500 completed contracts. The results of two empirical studies support the assertion. Both Kirk Payne and Scott Heise established that once a contract is 20 percent complete, the cumulative Cost Performance Index (CPI) does not change by more than 10 percent; in fact, in most cases it only worsens. (For example, in April 1990, the A-12 program was 37 percent complete and reported a CPI of 0.77. By September, the program was 47 percent complete and its CPI was 0.72.)

As shown in Equation 1, the Cost Performance Index is a ratio of BCWP to ACWP.

$$\text{CPI} = \text{BCWP} / \text{ACWP}$$

A CPI that is less than 1 means that for every dollar spent, less than one dollar of work is accomplished. It follows that when the cumulative CPI is less than 1, the contract is experiencing a cost overrun, and because an unfavorable cumulative CPI only worsens, a contract is not likely to recover from a cost overrun.

Therefore, if the predicted overrun at completion is less than the overrun to date, the contractor's estimated final cost of the contract (EAC) is unrealistically optimistic. This study further establishes these results by examining the cost overrun history on 64 completed contracts extracted from the Defense Acquisition Executive Summary (DAES) database.

Methodology

The DAES database has received summary data on completed contracts since 1977. Presently, data is summarized from Cost Performance Reports by government program offices and sent to the Office of the Under Secretary for Acquisition as quarterly DAES Reports. The database is a fairly detailed source of information on the cost performance of U.S. defense acquisition contracts. It is also reasonably accurate because most of the contracts in the database are C/SCSC compliant.

For this study, a sample of 64 completed contracts was extracted from the database. Although the sample was purely judgmental, it is considered sufficiently rich to generalize to any C/SCSC-compliant defense contract. Table 1 shows cost overrun data by various categories considered relevant to this study.

Based on the Under Secretary's assertion and the results of prior research, four hypotheses were tested (Table 2). For Hypothesis 1, the average final cost overrun in dollars

(FCO\$) exceeds the average cost overrun to date (CO\$). Hypothesis 2 is the same, except the overruns are expressed in percentages. If these hypotheses are correct with statistical significance, then recoveries from cost overruns are improbable with a certain level of confidence. For this study, the hypotheses were tested at the 95 percent level of confidence.

Based on the results of our prior research involving estimates at completion, it was expected that the results of the testing may be sensitive to the contract completion point and other factors specific to the contracts in the sample. Therefore, the hypotheses were systematically tested at nine contract completion points (10 to 90 percent at 10 percent increments) for various categories within the sample. The categories examined were the contract type (fixed price, cost), the contract phase (development, production), the generic type of weapon system, (air, ground, sea), and the armed forces service that managed the contract (Air Force, Army, Navy).

Table 1. Final Cost Overrun on 64 Completed Contracts

Contract Category	Number	Overrun (\$Millions)			Overrun (Percent)		
		Avg	Min	Max	Avg	Min	Max
All	64	36	-3	493	18	-3	109
Army	28	21	-3	46	20	-3	46
Air Force	18	49	-2	407	19	-1	109
Navy	18	47	0	493	13	0	46
Air	43	45	-3	492	18	-3	109
Ground	13	23	7	42	21	5	45
Sea	8	12	0	36	12	0	38
Development	25	38	-2	407	21	-1	109
Production	39	35	-3	493	16	-3	46
Cost	23	41	-2	493	14	-1	46
Price	41	34	-3	407	20	-3	109

The remaining hypotheses are related to the results of the referenced CPI stability studies which established that the cumulative CPI tends to worsen from the 20 percent completion point. Here the hypothesis was that the average cost overrun tended to increase. To test this hypothesis, the average cost overrun (CO) was regressed against percent complete (x):

$$CO = a + \beta x$$

Table 2. Hypotheses

Hypothesis	Interpretation
H1: $FCO\$ > CO\$$	Recoveries from cost overruns (\$) are improbable
H2: $FCO\% > CO\%$	Recoveries from cost overruns (%) are improbable
H3: $\beta\$ > 0$	Cost overruns (\$) tend to increase
H4: $\beta\% > 0$	Cost overruns (%) tend to increase

If the resulting slope coefficient (β) is positive with statistical significance, then the hypothesis is accepted, which means that cost overruns tend to increase. In Hypothesis 3, the average cost overrun was in dollars; in Hypothesis 4, the average cost overrun was a percent. As with Hypotheses 1 and 2, Hypotheses 3 and 4 were tested on the entire sample and on various categories of the sample.

Equations 3 and 4 define the current cost overrun and final cost overrun in dollars. Equations 5 and 6 define the overruns as percentages.

$$\text{Current Overrun (CO\$)} = \text{Cum ACWP} - \text{Cum BCWP}$$

$$\text{Final Overrun (FO\$)} = \text{Final ACWP} - \text{BAC}$$

$$\text{Current Overrun Percent} = 100^* (\text{CO\$}/\text{Cum BCWP})$$

$$\text{Final Overrun Percent} = 100^* (\text{FO\$}/\text{BAC})$$

The cost overruns were averaged for each category of the sample by dividing the number of contracts in that category into the total overrun for that category. The averaging was done at various stages of completion ranging from 10 to 100 percent complete, where percent complete was defined as follows:

$$\text{Percent Complete} = 100^* (\text{Cum BCWP}/\text{BAC})$$

Data earlier than the 10 percent completion point were not considered sufficiently reliable. It can take as long as one year from contract award for the contractor to demonstrate C/SCSC compliance. Until then the data on the Cost Performance Report is suspect.

Results

As shown in the remaining tables, the hypotheses were generally confirmed at the 95 percent level of confidence. Table 3 shows the results of testing Hypotheses 1 and 2 on the entire sample of 64 contracts. Recoveries from cost overruns expressed in either dollars or as a percentage are improbable, especially cost overruns experienced between the 10 to 70 percent completion points. Between these points the difference between the final cost overrun and the overrun to date was statistically significant at confidence levels well above 95 percent. After the 70 percent completion, the current overrun percent is necessarily much closer to the final overrun percent because monthly expenditures typically decrease as the work nears completion.

Hypotheses 1 and 2 were also generally confirmed for the categories of the sample examined. In short, recoveries from cost overruns on defense contracts are highly improbable, regardless of the contract's type, the contract's phase, the type of weapon system, or the armed forces service that managed the contract.

Table 4. Cost Overruns Tend to Increase

Contract Categories	Cost Overrun (\$ Millions)			Cost Overrun (Percent)		
	Slope (β)	SE	t	Slope (β)	SE	t
All	0.325	0.020	16.13	0.198	0.009	22.09
Army	0.186	0.013	14.27	0.234	0.016	15.08
Air Force	0.407	0.034	12.11	0.180	0.005	36.11
Navy	0.459	0.021	21.38	0.159	0.013	12.20
Air	0.416	0.022	18.71	0.210	0.010	20.30
Ground	0.168	0.024	7.06	0.193	0.018	11.00
Sea	0.095	0.008	12.57	0.139	0.013	10.37
Development	0.318	0.024	13.37	0.232	0.008	29.12
Production	0.330	0.019	17.18	0.176	0.012	15.08
Cost	0.393	0.018	21.40	0.166	0.015	10.88
Price	0.287	0.022	12.93	0.215	0.006	34.48

SE = Standard error of slope coefficient with the intercept forced to zero;
t = t statistic; $t_{\alpha} = .05 \text{ df } = 8 = 1.895$

Table 4 shows the results of testing Hypotheses 3 and 4, and confirms that cost overruns on defense contracts tend to increase. The slope coefficients were greater than zero with statistical significance for the entire sample, and for each category of the sample that was examined.

Managerial Implications

The results of this research show that recoveries from cost overruns on defense contracts are highly improbable, and that cost overruns tend to worsen as a defense contract proceeds to completion. This was found to be true regardless of the type or phase of the contract, the type of weapon system, or the armed forces service that managed the contract. The results are consistent with the results of related research involving the stability of the Cost Performance Index, and confirm the observations of senior analysts at the Office of the Under Secretary of Defense for Acquisition.

These results have strong managerial implications for the project manager: more realistic

projections of the final costs are needed. When the projected overrun at completion is less than the overrun to date, the projected overrun at completion is too optimistic. Former Under Secretary of Defense for Acquisition Donald J. Yockey commented in 1991 on this issue:

We can't afford to underestimate, sit on, or cover up problems in any program—at any time—at any level. They must be brought forward. This includes not just "show stoppers" but also "show slowers." I can't stress this strongly enough.

Without more realistic estimates, senior management may be lulled into a false sense of security about their programs and fail to take appropriate action to correct problems.

Wayne Abba and Gary Christle, senior analysts at the Office of the Under Secretary of Defense for Acquisition, have commented that although recoveries from cost overruns are improbable, they are possible, especially if management pays proper attention to

them. With proper attention adverse variances have been reversed.

Proper attention requires a timely and disciplined analysis of variances as they are identified. It also requires a proper culture. A "shoot the messenger" culture was partly responsible for the delayed reporting of adverse information on the A-12 program. Accordingly, senior management should make every effort to cultivate a healthy attitude regarding variance reporting. Managers are necessarily advocates of their projects. But this does not mean suppressing or delaying the communication of adverse information about their projects to senior decision-makers.

It is not known if recoveries from cost overruns on non-defense projects are also improbable. Perhaps additional research can explore this issue. Technical and political problems that contribute to cost overruns on defense projects may not be relevant to non-defense projects; however, the "shoot the messenger" culture involved in the A-12 program is certainly a potential problem in non-defense industries.

A related "cultural" factor that contributed to the cancellation of the A-12 was the natural optimism of senior management. In testi-

mony before Congress, Navy Secretary of Defense Garret characterized the senior managers involved in the A-12 program as "can do" people who did not admit to failure lightly. Although optimism has its place, it can be dangerous when it blinds the manager to the truth.

Finally, social scientists like Barry Staw have extensively documented many real-world examples of "escalation error." In these examples, the decision-maker is extremely reluctant to cancel an ongoing project or switch to an alternative, despite excessive overruns or other compelling evidence that the project has failed or that the alternative is superior to the present course of action. In some cases, the manager chooses to escalate commitment to the project by increasing the spending on the project. Researchers have attributed such behavior to psychological factors such as a myopic "can do" attitude or a need to "save face."

More recently, Chandra, Bushman and Dickhaut have suggested that escalation error is caused by the manager's desire to protect his/her reputation in the managerial labor market. Given the adverse economic consequences of cost overruns, additional research in this area is needed.

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PROGRAM CONTROL ON THE TROPICAL RAINFALL MEASURING MISSION

by Dorothy J. Pennington and Walter Majerowicz

The Tropical Rainfall Measuring Mission (TRMM), an integral part of NASA's Mission to Planet Earth, is the first satellite dedicated to measuring tropical rainfall. TRMM will contribute to an understanding of the mechanisms through which tropical rainfall influences global circulation and climate. Goddard Space Flight Center's (GSFC) Flight Projects Directorate is responsible for establishing a Project Office for the TRMM to manage, coordinate and integrate the various organizations involved in the development and operation of this complex satellite. The TRMM observatory, the largest ever developed and built inhouse at GSFC, includes state-of-the-art hardware. It will carry five scientific instruments designed to determine the rate of rainfall and the total rainfall occurring between the north and south lati-

tudes of 35 degrees. As a secondary science objective, TRMM will also measure the Earth's radiant energy budget and lightning.

The complexities of managing an inhouse project are magnified by many non-GSFC interfaces, as shown in Table 1. The TRMM Project Office is responsible for managing the integration of all segments of this complex activity and providing a cohesive team that will deliver a fully functioning observatory within budget and schedule constraints. These interfaces require careful management and coordination of technical, schedule and budget elements. While the project office provides overall program planning, direction and control, the subsystem managers and instrument suppliers implement project requirements at a detailed level.

Table 1. TRMM Organization Responsibilities

Component	Responsible Organization
Project Management	TRMM Project
Observatory Subsystems	Engineering Directorate/numerous aerospace companies
Precipitation Radar (PR)	Japan/ NASDA/Toshiba
TRMM Microwave Imager (TMI)	TRMM Project/Hughes
Visible Infrared Scanner (VIRS)	TRMM Project/Santa Barbara Research Center
Clouds and Earth's Radiant Energy System (CERES)	EOS/Langley Research Center/TRW
Lightning Imaging Sensor (LIS)	TRMM Project/Marshall Space Flight Center
TRMM Science Data and Information System (TSDIS)	Earth Sciences Directorate/General Sciences Corporation
Mission Operations	Mission Operations and Data System Directorate
H-II Launch Vehicle and Launch Services	Japan/NASDA
Science Team	Earth Science Directorate, U.S. Universities, JPL, NOAA, Japan, Australia, Israel, France, Taiwan, Great Britain

One immediate challenge to securing a successful TRMM mission is implementing program control systems that will ensure an August 1997 launch from Tanegashima Space Center, Japan. The August 1997 launch is critical; if TRMM is not launched on time, high levels of solar activity forecast for the late 1990s would result in a reduced mission life. This constraint, along with the limitation of biannual launch windows at the Tanegashima Space Center, places top priority on schedule performance, but not at the expense of technical excellence, safety or cost.

Program Control Overview

The TRMM Program Control staff has established a comprehensive Program Control System that includes schedule management, financial management, configuration management and risk management. The Program Control System is not simply a computer program. Rather, it consists of a series of checks and balances in each of these areas that are designed to keep the entire management system integrated, as shown in Figure 1. Four monthly reports reflecting analyses in the areas of schedule, finance, general

business and risk management are generated by the TRMM program control staff. These reports, called the Program Control Monthly Status Reports (PCMSR), are distributed to TRMM technical and resources management and provide a current, complete analysis of all business issues and concerns. TRMM also conducts monthly status reviews with each of the subsystem, instrument and element managers. During these reviews, each manager is allocated approximately 30 minutes to present technical, cost, schedule and manpower issues and concerns to the TRMM Project Manager. The importance placed on communication, whether through these reviews or in the PCMSR, is one of the key reasons behind the success of the Program Control System.

A major element of the Program Control System is the logic network. Using the project work breakdown structure, the project planners developed an end-to-end network that was baselined shortly after the TRMM System Concept Review. This network, in conjunction with the mission specifications and agreements, provided the foundation for pro-

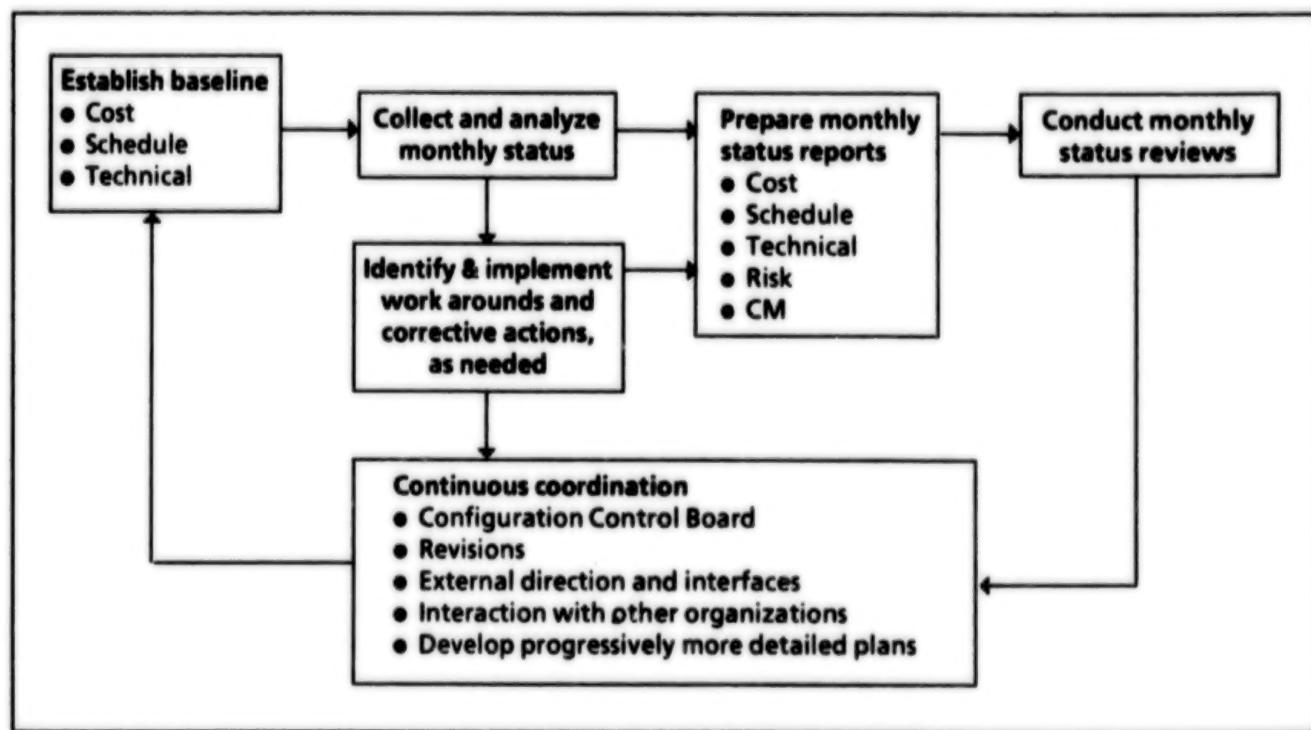


Figure 1. Program Control Process

ject management to focus on the preparation of the budget estimates. Careful consideration was given to technical and schedule risks and tradeoffs while attempting to determine annual funding requirements. After the technical, schedule and cost baselines were established, the TRMM Configuration Control Board (CCB) was set up to systematically consider all changes to the baselines. Finally, the risk management report was initiated by the Program Control staff to provide project management with an ongoing early warning system. Through this mechanism, actions to resolve cost, manpower, schedule and technical problems are quickly identified and implemented. Frequent communication between project management, subsystem managers, instrument suppliers and the program control staff is the key to maintaining these effective management systems.

Schedule Management

The scheduling function is centralized at the project level. The scheduling staff is assigned to the project office and coordinates with both GSFC and outside organizations responsible for the development of the TRMM spacecraft, instrument, and ground segments as well as overall system integration and test (I&T).

The TRMM Program Control staff has developed a comprehensive logic network for TRMM that integrates key work tasks and milestones from all elements within the TRMM system. For work being performed at GSFC, the schedulers prepare the subnetworks in coordination with the responsible subsystem and element technical managers. For work being performed outside of GSFC, schedule data is received from the contractors' scheduling systems and incorporated into the TRMM schedule data base.

A sample portion of the logic network is contained in Figure 2. The information contained in the activity boxes or "nodes" identifies the task description, activity duration in

work days, and total slack (the amount of time an activity or event can be delayed before it impacts launch readiness). With the use of TRMM's automated scheduling system for developing and maintaining the logic network, barcharts are easily generated. The bar chart corresponding to the logic network sample presented in Figure 2 is shown in Figure 3. These detailed schedules are "rolled up" to an intermediate level in order to summarize the schedule information for management. Figure 4 depicts how the Thruster detailed schedule is summarized within the Reaction Control Subsystem (RCS) Intermediate Schedule. This "roll-up" or schedule summarization capability, combined with the precedence relationships among the activities in the logic network, provide the framework to properly manage the vertical and horizontal schedule integration and traceability on TRMM.

For effective Program Control of TRMM, maintaining a schedule baseline is as important as maintaining a technical and cost baseline. Moreover, proper configuration management of the TRMM schedule is vital in order to accurately assess the impact of changes. TRMM's formal schedule baseline is identified in the TRMM Project Schedule Baseline Document (PSBD). The PSBD consists of three parts: major project milestones, project control milestones and the Observatory integration and test schedule. The schedule for these milestones can only be changed with the approval of the TRMM Configuration Control Board.

The major project milestones provide the framework for overall planning and scheduling for the TRMM spacecraft segment, instrument segment, and ground segment developments, system integration and test, shipping and delivery and launch site preparations. These milestones, depicted at the top of the Master Schedule (see Figure 5) consist of the System Concept Review (SCR), Preliminary Design Review (PDR), Critical

TRMM THRUSTER LOGIC NETWORK

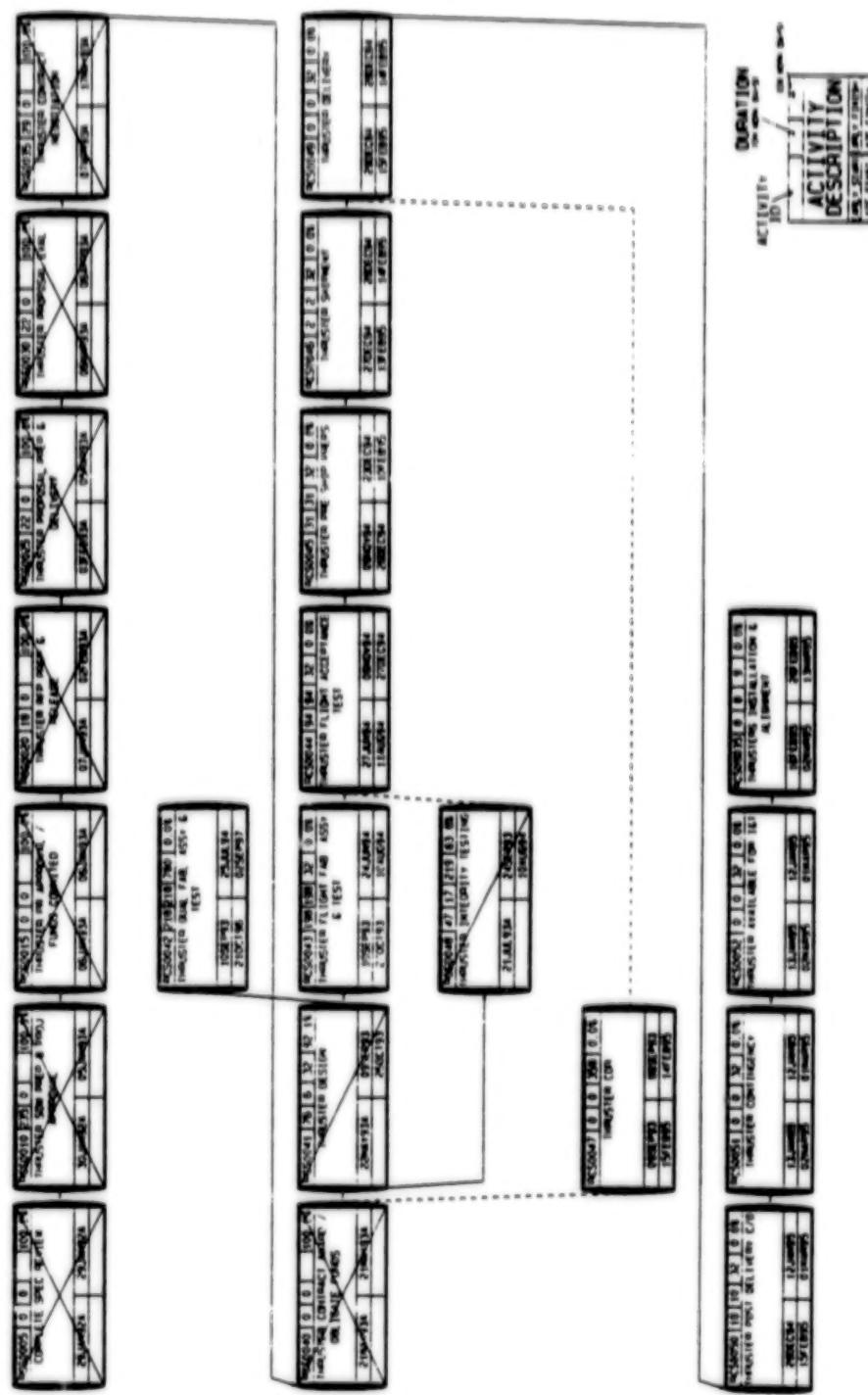


Figure 2. RCS Thruster Logic Network Diagram

PROGRAM CONTROL ON THE TROPICAL RAINFALL MEASURING MISSION

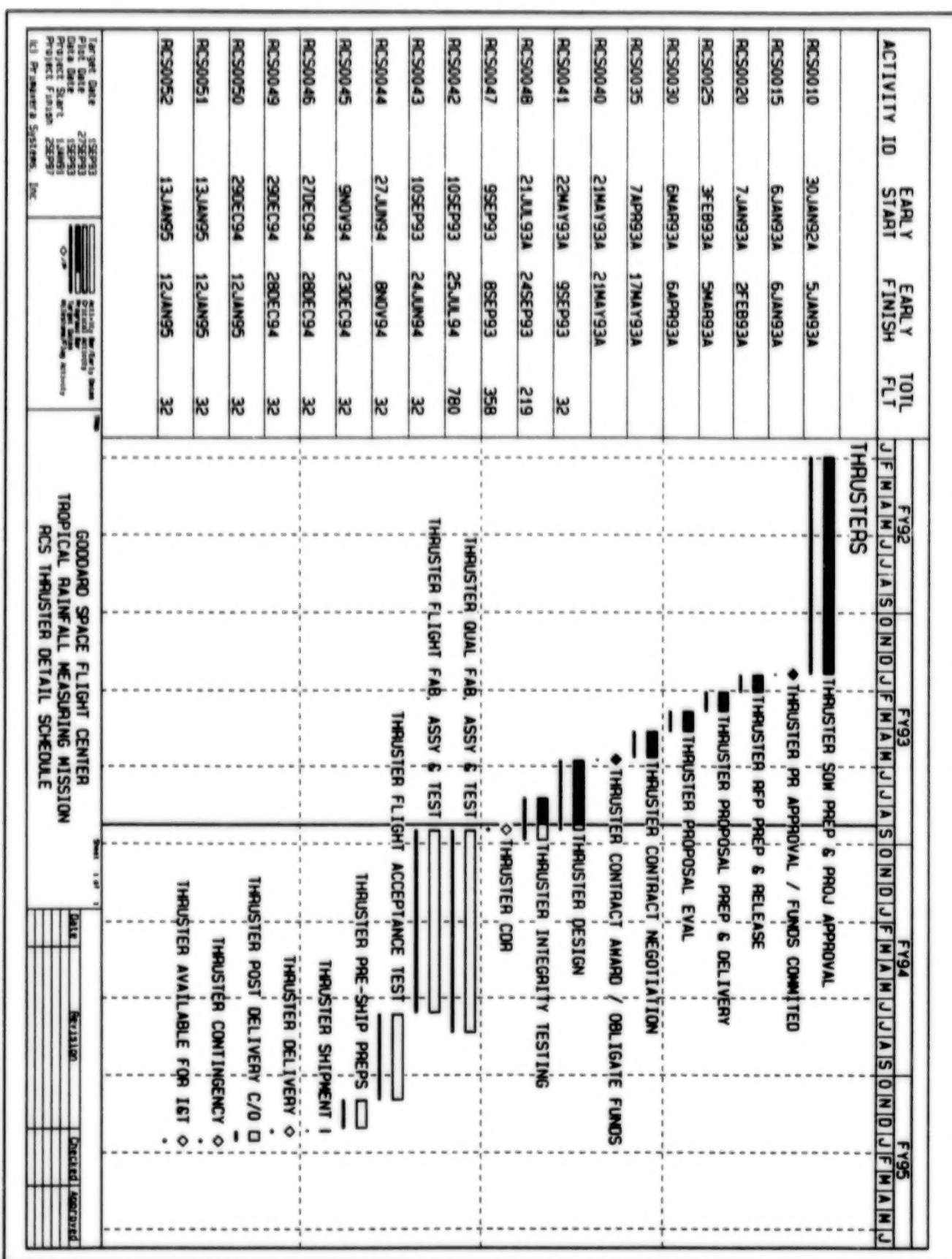


Figure 3. RCS Thruster Detailed Schedule Barchart

READINGS IN PROGRAM CONTROL

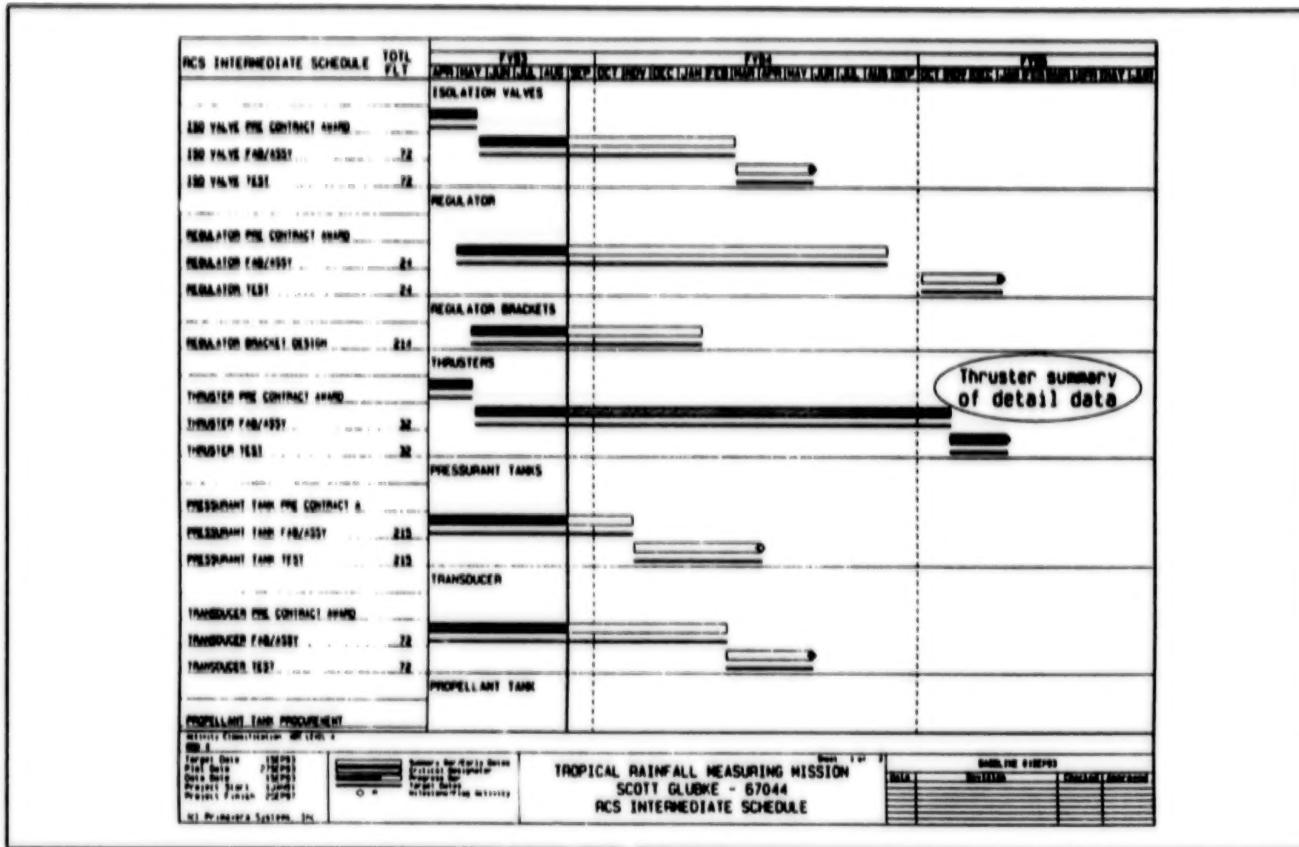


Figure 4. RCS Intermediate Schedule (1 of 2)

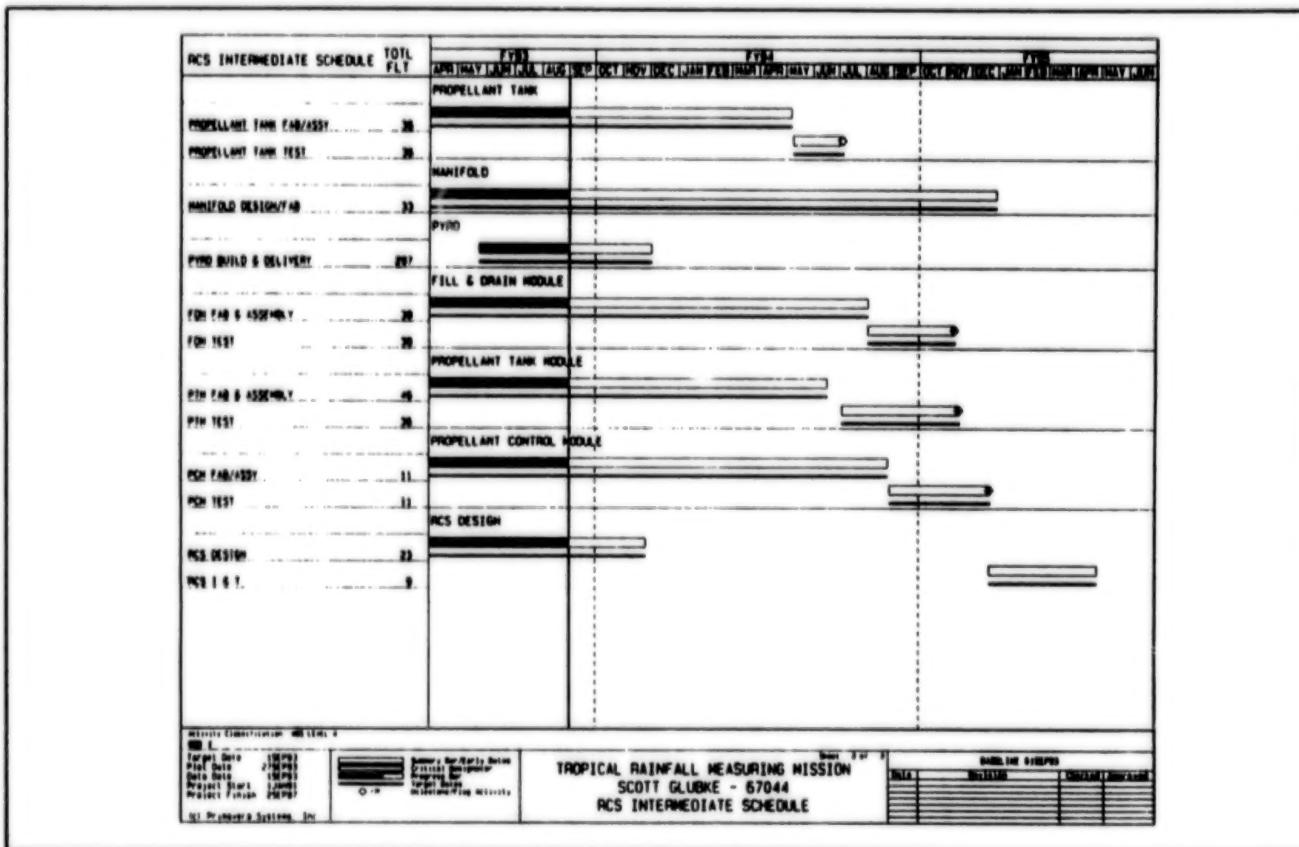


Figure 4. RCS Intermediate Schedule (2 of 2)

Design Review (CDR), Pre-Environmental Test Review (PER), Pre-Shipment Review (PSR), and the Launch Readiness Review.

The project control milestones are events which the TRMM Project Office considers critical. These include, but are not limited to, interface milestones such as the delivery of

hardware or software between TRMM organizational elements. Control milestones can also represent the completion of major stages of work within a given subsystem or element. More importantly, they are commitments by the responsible organizations to the TRMM Project Office to accomplish these events as planned.

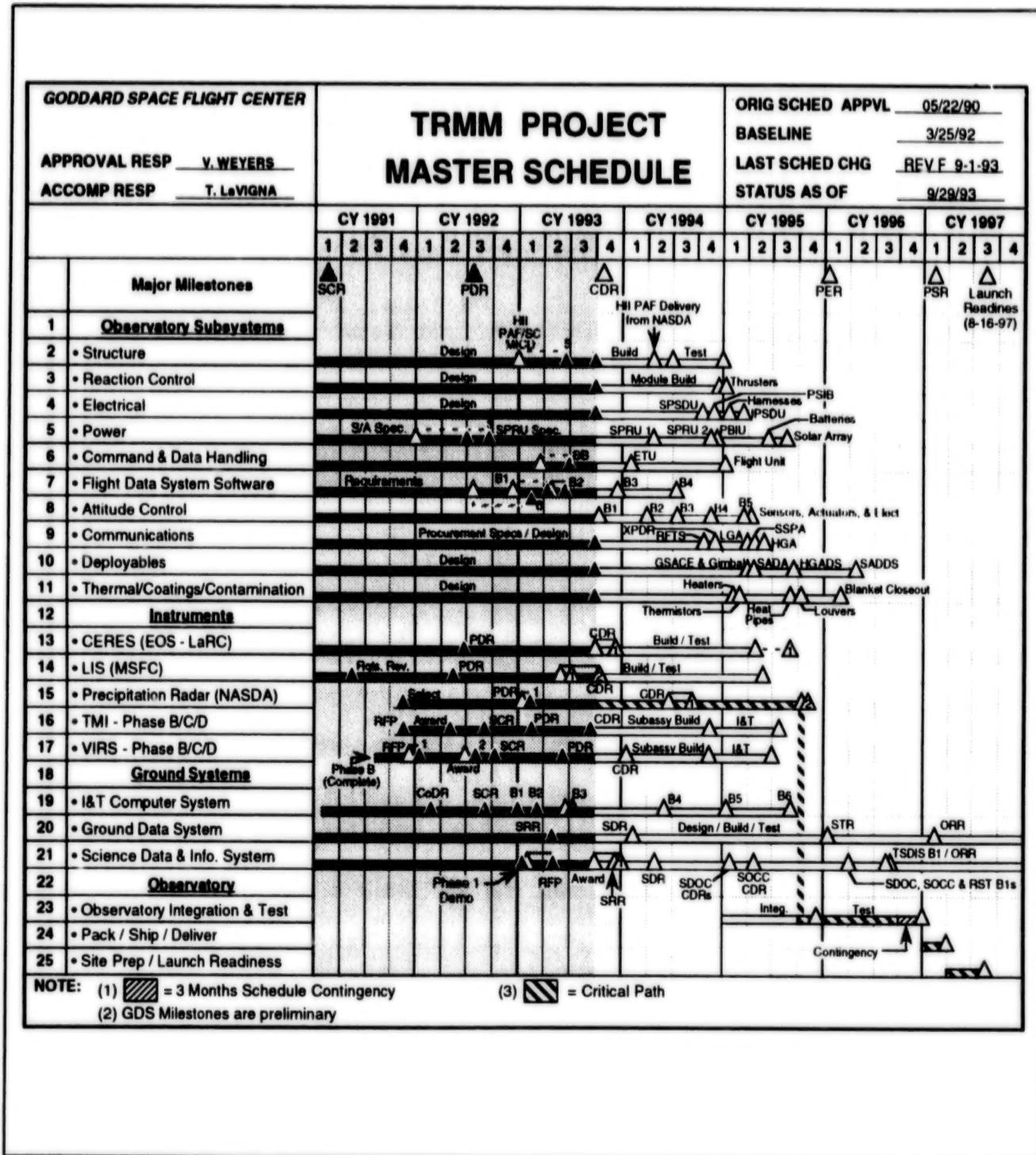


Figure 5. TRMM Project Master Schedule

Next, the TRMM I&T schedule is included in the PSBD because it establishes the need dates for flight hardware and software. Considerable emphasis was placed on establishing the I&T schedule soon after the SCR in February 1991. Moreover, because all of the TRMM elements ultimately come together during integration and test, the I&T schedule has become the "hub" of the overall scheduling process. It is a key planning tool for all of the elements of the spacecraft, instrument and ground segments.

Since the logic network is a continuously evolving tool, it is not directly contained in the PSBD—only the project control milestones are. However, the logic network supports the schedule baseline in that a target version of the network is maintained against which the current status is compared. This concept is illustrated in the sample barchart presented earlier (see Figure 4). The compressed black line below each activity bar or milestone represents the schedule baseline at the detailed work task level. This provides a correlation between the current schedule and the baseline. Unilateral changes to the logic network by the responsible subsystem or technical managers are permitted, provided they do not impact the project control milestones or necessitate rephasing of the budget.

Schedule status accounting on the TRMM Project occurs formally each month. Work already underway or activities that should have started or been completed since the last accounting period are statused by determining the percentage of work accomplished, the amount of time remaining to complete a task, or the new expected finish date of a task. For the work being performed at GSFC, the responsible subsystem technical managers are interviewed by the schedulers in order to obtain schedule status. In this way, the schedulers receive not only the status, but also the rationale and issues affecting the

status. Once the raw status is input into the logic network data base, it is processed, analyzed and verified. This allows schedule issues to be identified, resolved or addressed before status is formally reported in the TRMM Monthly Project Review. For TRMM's scientific instruments, schedule status is received from the instrumentors each month and analyzed prior to incorporation into the logic network.

The key driver in the TRMM schedule is the August 16, 1997 launch readiness date. In addition to monitoring the actual progress of work toward launch readiness, the TRMM schedulers conduct a careful analysis of schedule slack. Total slack is a specific, quantitative and easily understood measure of schedule health. Figure 6 depicts the TRMM Total Slack Summary, which presents a high level overview of TRMM progress for a given month. The chart highlights the key elements for the spacecraft, instrument and ground segments. Each month the total slack for the worst case item within each TRMM element is elevated to the total slack chart. It is compared to total slack from the previous month, as well as the total slack for that item in the schedule baseline. The benefit of the total slack chart is that TRMM project managers can see the overall health of the TRMM project schedule at a glance.

The schedule products such as bar charts and network diagrams are important Program Control tools for TRMM. When combined with a formal status process, they enable the TRMM Project Office to assess the progress of the TRMM schedule. As an early warning mechanism, the scheduling system provides a means to detect potential schedule problems, implement workaround plans, or take corrective action in order to mitigate problems. Scheduling products are tailored to various members of the TRMM team. Tools such as the Total Slack Chart and the Intermediate Schedules provide a way to summa-

Element	Baseline Delivery	Master Schedule - REV F ³ Total Slack	Aug 1993 Total Slack	Sep 1993 Total Slack	Driver
Spacecraft Structure	12-30-94	+12 Days	+12 Days	+12 Days	Aft Skirt/Central Cylinder
Reaction Control	12-21-94	+14 Days	+14 Days	+14 Days	Propellant Control Module
Electrical	11-30-94	+53 Days	+53 Days	+53 Days	PSIB
Power	8-18-95	+30 Days	+30 Days	+30 Days	Solar Array Panels
C & DH	1-6-95	+83 Days	+83 Days	+83 Days	C&DH Flight Unit
FDS Software	12-15-93	+83 Days	+83 Days	+83 Days	FDS Build #3
Attitude Control	10-8-93	+32 Days	+32 Days	+32 Days	ACS S/W Build 1
Communications	5-26-95	+46 Days	+46 Days	+46 Days	High Gain Antenna
Deployables	4-24-95	+30 Days	+30 Days	+30 Days	SADDS (Flight Wings)
Thermal	2-28-95	+33 Days	N/A	+33 Days	Thermistors
LIS	6-1-95	+53 Days	+53 Days	+53 Days	Electronics Assembly
CERES	9-1-95	+29 Days	+29 Days	+29 Days	Biaxial Scan Assembly
Precipitation Radar ⁴	10-25-95	+12 Days	+4 Days	+4 Days	Transmitter / Receiver
TMI	8-1-95	+32 Days	+32 Days	+32 Days	Receivers
VIRS	7-1-95	+42 Days	+42 Days	+42 Days	Electronics Module
TSDIS	8-14-95	+35 Days	+35 Days	+35 Days	Contract Award
IAT Computer Systems	6-9-94	+41 Days	+88 Days	+41 Days	IATCS Build 04
Observatory IAT	10-9-95	+12 Days	+4 Days	+4 Days	Precipitation Radar

Figure 6. TRMM Total Slack Summary

rize a tremendous amount of detailed schedule data for TRMM project management. With this information, management can focus on the key issues, critical paths and potential workarounds. At the working level, detailed schedule bar charts and logic network diagrams are excellent planning tools. In summary, the TRMM scheduling system provides reliable information to all levels of users.

Financial Management

A key feature of the Program Control System is cost and schedule integration. As with the scheduling staff, the financial staff is centralized at the project level, although other GSFC organizations also provide financial support for TRMM subsystem managers. The main duty of the financial staff is budget formulation and execution. The logic network schedule serves as a basis for TRMM budget planning. Based on a detailed integration

and test sequence, need dates for flight hardware and software have been precisely identified. Budgets were formulated against the timeframe reflected in the schedules, as illustrated in Figure 7.

By integrating cost and schedule planning, the project office has the capability to perform what-if budget and schedule simulations. Civil servant manpower and travel budgets were also developed using the schedule as a guide in determining the correct phasing of requirements. In a dynamic budget environment, the TRMM Project is quickly able to isolate the impact of schedule delays, manpower shortages and travel cuts on the budget requirements. Similarly, when budgets are reduced, the integrated cost and schedule information provides a framework to quickly determine the scope of work that can be reprogrammed without having undesirable effects on launch readiness.

The TRMM Project has already used this system to identify numerous planned early-year, high-cost component purchases that could be deferred to later years, thereby alleviating funding problems without jeopardizing the integration and test schedule.

Close coordination between the subsystem and element managers and the TRMM financial staff ensures timely and accurate preparation of budget estimates and procurement requests. Since TRMM is an inhouse project, the procurement activities are not focused on several large prime contracts, as typically found in other GSFC projects. Instead, the financial and procurement staffs are responsible for purchasing the components, parts and instruments that will come together as a complete observatory. These extensive procurement activities require detailed planning and coordination to remain on schedule.

The budget was developed for these procurements and supporting effort as discrete items at the Job Order Number (or work package)

level. The budget requirements were then "rolled-up" through the project work breakdown structure by month and fiscal year. This summarization ensures that budget data submitted to NASA Headquarters is based on the detailed estimates for the entire project. As part of the financial system, the TRMM financial staff has developed an extensive contingency tracking system. Details of all changes in the budget baseline are maintained in the contingency (management reserve) tracking system as shown in the summary portion of Table 2. This provides a complete audit trail of all items funded from the contingency line item.

In addition to budgeting and procurement responsibilities, the financial staff analyzes contractor financial performance and ensures that other members of the TRMM project team are kept abreast of financial issues and concerns. The TRMM Microwave Imager contract includes requirements for modified Performance Measurement System (PMS) reporting.

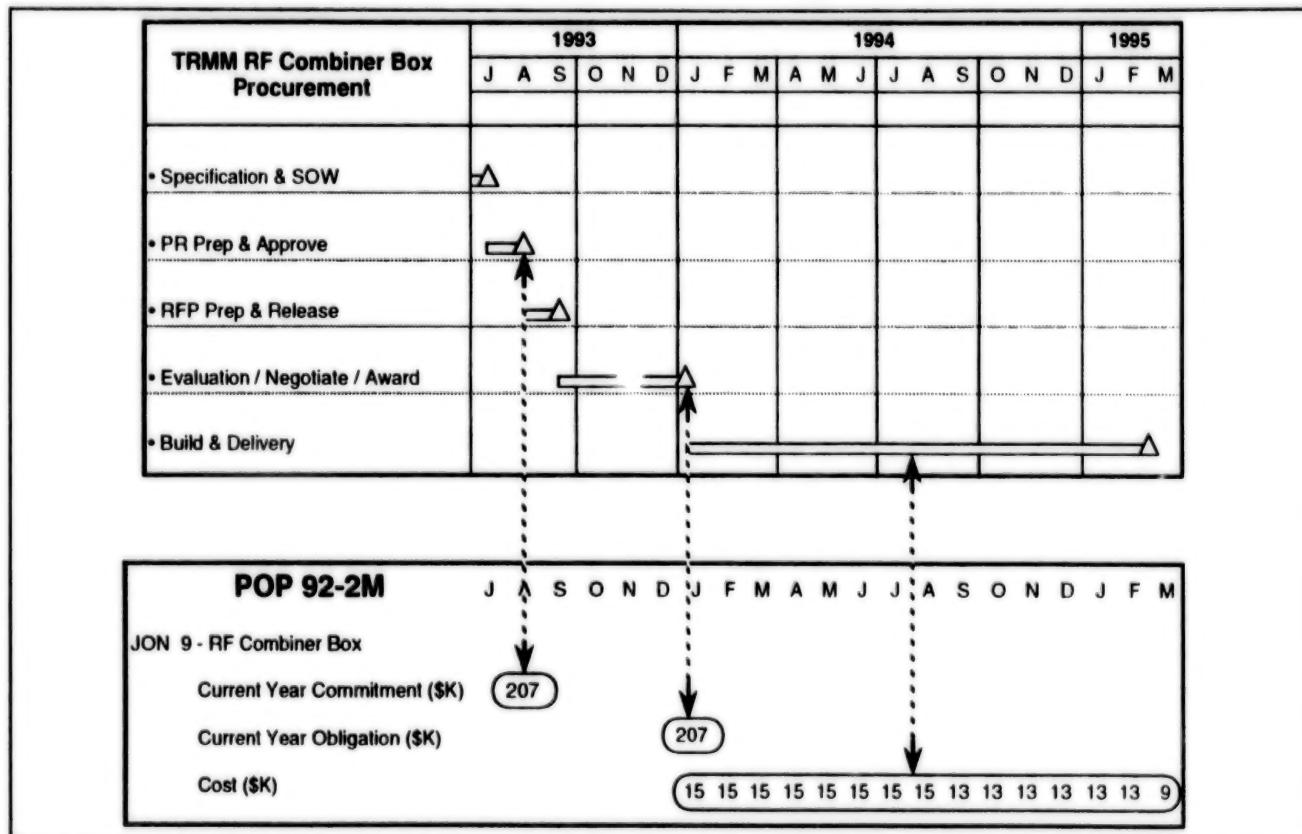


Figure 7. TRMM Cost/Schedule Integration

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Table 2. Contingency Tracking System

TRMM PROJECT -- CONTINGENCY TRACKING SYSTEM										
ENCUMBRANCE SUMMARY:										
CAT	DESCRIPTION	POP	FY 91	FY 92	FY 93	FY 94	FY 95	FY 96	FY 97	TOTAL
1	REPHASE/RELOCATE	ALL	0	455	387	1559	-3936	-193	1728	0
2	ADJ TO PROPOSAL/NEGOTIATED/LATEST ESTIMATE	ALL	60	1546	-2543	2913	-945	-1719	-562	-1250
3	MINOR/MISC (EACH ACTION < \$100K)	ALL	201	-180	1129	-109	326	-47	149	1469
4	ITEMIZED									
4 POP	05/28/93 MSSN OPS	SIMULATOR SPPT (CEAS/NMOS)	93-1			103	162	210	475	
4 POP	05/28/93 S/W MGMT	IV&V TASK	93-1			1050	375	250	125	1800
4 POP	05/28/93 TEST	ILM DPL OF SUBSYS COMPONENTS	93-1			-6	-734	-207	48	-1148
4 POP	05/28/93 PROD ASSUR	PARAMAX (INCREASE REQ)	93-1			137	229	166	532	
4 OB-0035	06/3/93 POWER	PSE TECH CHG	92-2M			-100	75	-650	-675	
4 MEMO	01/1/93 POWER	SOLAR ARRAY	93-1			576	-2635	-1444	-44	-3594
4 OB-0001	06/13/91 POWER	G&A SA	92-1			100	967	966	866	2899
4 POP	10/26/92 POWER	PSE DECREASE	92-2M			-100	-95	230	-195	
4 OB-0066	12/18/92 RCS	THRUSTER CHANGE/ISO ADDTN	93-1			346	-115	-24	207	230
4 POP	05/28/93 ELEC	WIRE HARNESS PARTS (CCR & INCREASE)	93-1			195	462	638	68	1363
4 OB-0035	06/30/92 ELEC	PSE TECH CHG	92-2M			66	75	105	137	463
4 POP	10/26/92 ELEC	S/W CM	92-2M			-469	-200	-583	-623	-689
4 OB-0035	06/30/92 C&DH	PSE TECH CHG	92-2M			-583	-623	-1206	-1206	
4 OB-0013	04/26/92 C&DH	REMOVE 5 SIRTS	92-2			10	140	143	215	118
4 POP	05/28/93 FLIGHT S/W	FDS S/W SPPT	93-1			354	354	626	354	
4 MEMO	03/01/93 GRND SYS	GS PROJ SPPT	93-1			285	285	285	285	
4 MEMO	01/22/93 GRND SYS	GS HW & SW PURCHASE	93-1			160	160	160	160	
4 GN-0030	06/06/92 SPT GRND	PROTOTYPE BUDGET INCREASE	92-2M			25	36	48	60	242
4 POP	05/28/93 GRND SYS	EOSDIS SPPT/ERRO	93-1			-120	-160	-120	-400	
4 IN-0106	03/22/93 TMI	ANGULAR MOMENTUM COMPENSATION	93-1			418	418	418	418	
4 POP	05/28/93 VIRS	COOLER (INCREASE)	93-1			506	506	506	506	
4 POP	05/28/93 MPS	ROS TRANSFER W/O G/L	93-1			3338	3338	3338	3338	
4 POP	05/28/93 MPS	MPS TAX CHANGE	93-1			624	624	624	624	
SUBT 4				0	355	1193	736	39	3046	5993
TOTAL				261	2176	167	5098	-4516	1067	1939
										6212

On a monthly basis, the financial staff prepares a quick look analysis of the PMS data in the TRMM Program Control Monthly Status Report. Analyses are also prepared for other contracts and for fiscal activity.

Configuration Management

TRMM's integrated program control approach also closely aligns cost and schedule management with configuration management (CM) activities. TRMM's configuration management system provides a disciplined approach for controlling the changes to the requirements in hardware, software, performance, schedule and cost. Budget, schedule and technical requirements were established as integrated baselines early in the project's life. As changes to the established baselines occur, they are formally presented to the TRMM CCB.

The CCB, composed of technical and administrative representatives from each of the project disciplines, evaluates the positive or negative impact of each change on the bud-

get, schedule, and technical baselines. With this integrated, accurate approach to cost and schedule assessment, the impact of engineering changes can be quickly and thoroughly evaluated across the project. The TRMM Project Office has a goal to evaluate all changes within 45 days of the initial change request. A work progress indicator for the CM process has been incorporated into the Risk Management System.

Risk Management

Risk management is another key element of TRMM's integrated program control process. The Risk Management System emphasizes detection and resolution of problems in areas identified as having risk potential. The system allows managers to identify program risks and to implement alternate plans to mitigate the impact of unresolved problems, as shown in Figure 8. Cost, schedule and technical risk parameters have been identified for TRMM to quantitatively measure program health and ultimately program risk.

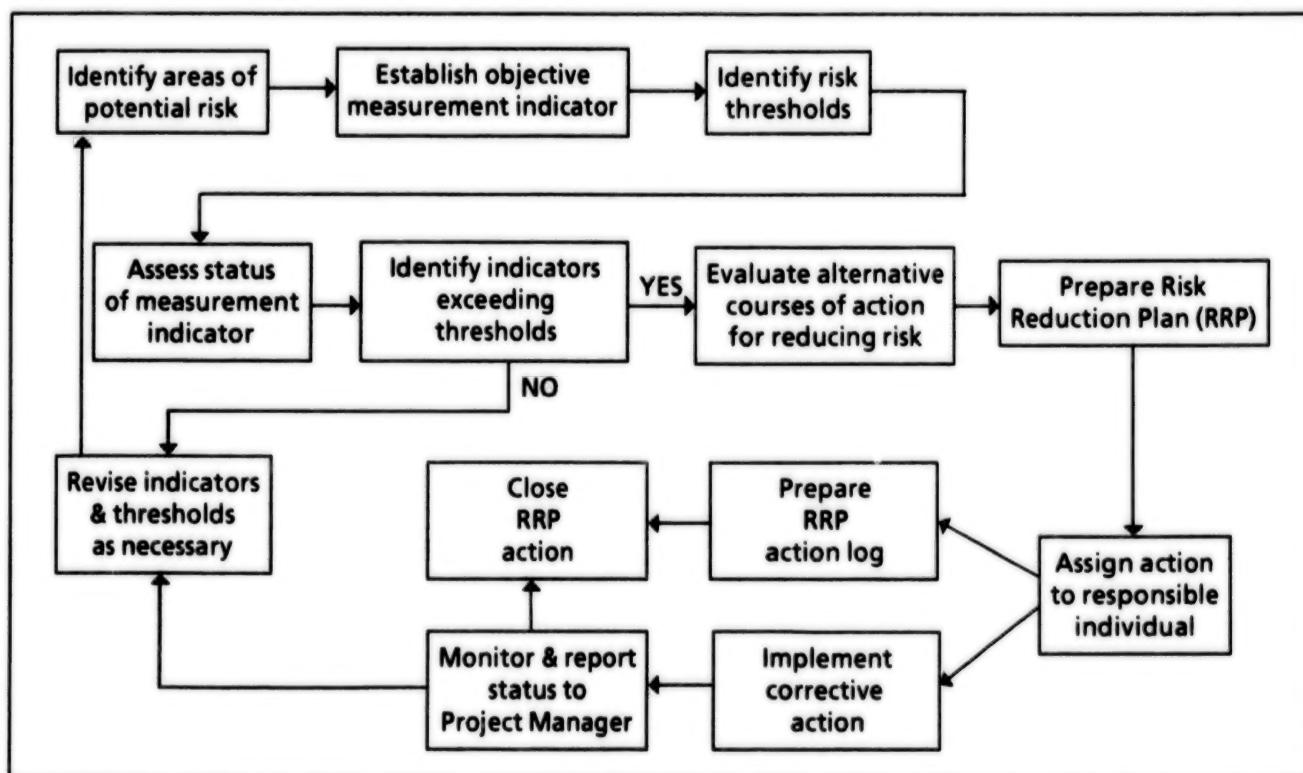


Figure 8. TRMM Risk Management Process

Figure 9 shows the elements of the project that are tracked in the monthly Risk Assessment Report. Technical indicators include power, mass, data rate and mission life. Management indicators include finance, schedule, configuration management, manpower and procurement. These risk indicators have been identified to provide a quantifiable goal against which progress is measured.

Each indicator has three tolerance levels or alert zones used to indicate the level of risk. First, risk is classified as a major impact if the indicator's performance reflects the existence or imminent threat of major problems, concerns or similar severe impacts upon accomplishment of project requirements. Second, the risk is identified as a potential impact if performance reflects the existence of problems, concerns or potential impacts on the project unless timely and effective action is taken. In the third category, the risk poses

no negative impact on meeting TRMM cost, schedule and technical requirements. When an alert zone threshold is passed, an analysis is conducted by the responsible manager to determine the cause of the problem and a corrective action plan is generated to restore the indicator to the desired state. The Risk Reduction Plan documents these products and provides an audit trail for the project to assign, track and close the corrective actions.

Figure 10 illustrates the risk indicator summary for the TRMM Configuration Change Requests. The project recognizes that failure to act upon change requests in a timely manner could affect the project's ability to accomplish cost and schedule goals. The alert zones reflect the project's goals for the disposition of all change requests in 45 days. The accompanying status shown in Figure 11 provides a monthly record of TRMM's performance against these pre-established thresholds.

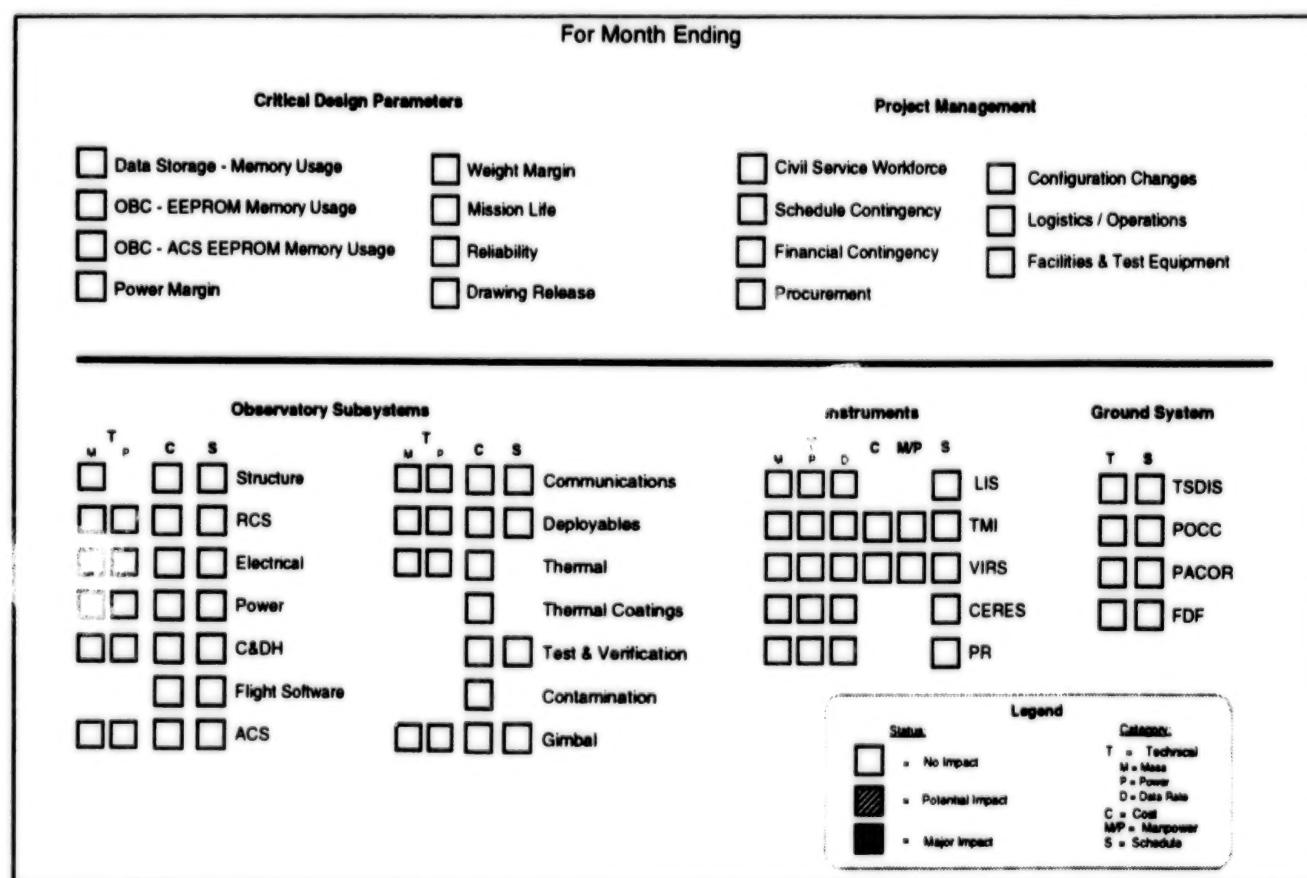


Figure 9. TRMM Risk Assessment Summary

Configuration Changes

Purpose: To track the status of engineering changes (Class I) in terms of timely action to avoid schedule and/or cost impact.

Data ground rules:

- Track age of Configuration Change Requests (CCRs)
- Change quantity measured by count of approved change logged into configuration control.

Alert zones:

<input type="checkbox"/> No Impact or	Age of CCR less than 45 days
<input checked="" type="checkbox"/> Potential Impact or	Age of CCR between 45 and 60 days
<input checked="" type="checkbox"/> Major Impact	Age of CCR over 60 days

Figure 10. TRMM (CCRs) Indicator Summary

When the assessment is unfavorable, a Risk Reduction Plan is generated (Figure 12) which analyzes the cause, impact and corrective action. The thresholds for the alert zones were set jointly by the responsible subsystem manager and the project manager and are intended to represent a reasonable goal for that indicator. These thresholds were sometimes adjusted several times in the preliminary months of the Risk Assessment Report until all parties felt that the appropriate goals were reflected.

Figure 13 shows the risk indicator for the RCS schedule slack. This indicator, used for all subsystems and instruments, tracks slack trend status. Each month, the actual slack is compared to pre-established thresholds and risk reduction plans are generated as needed.

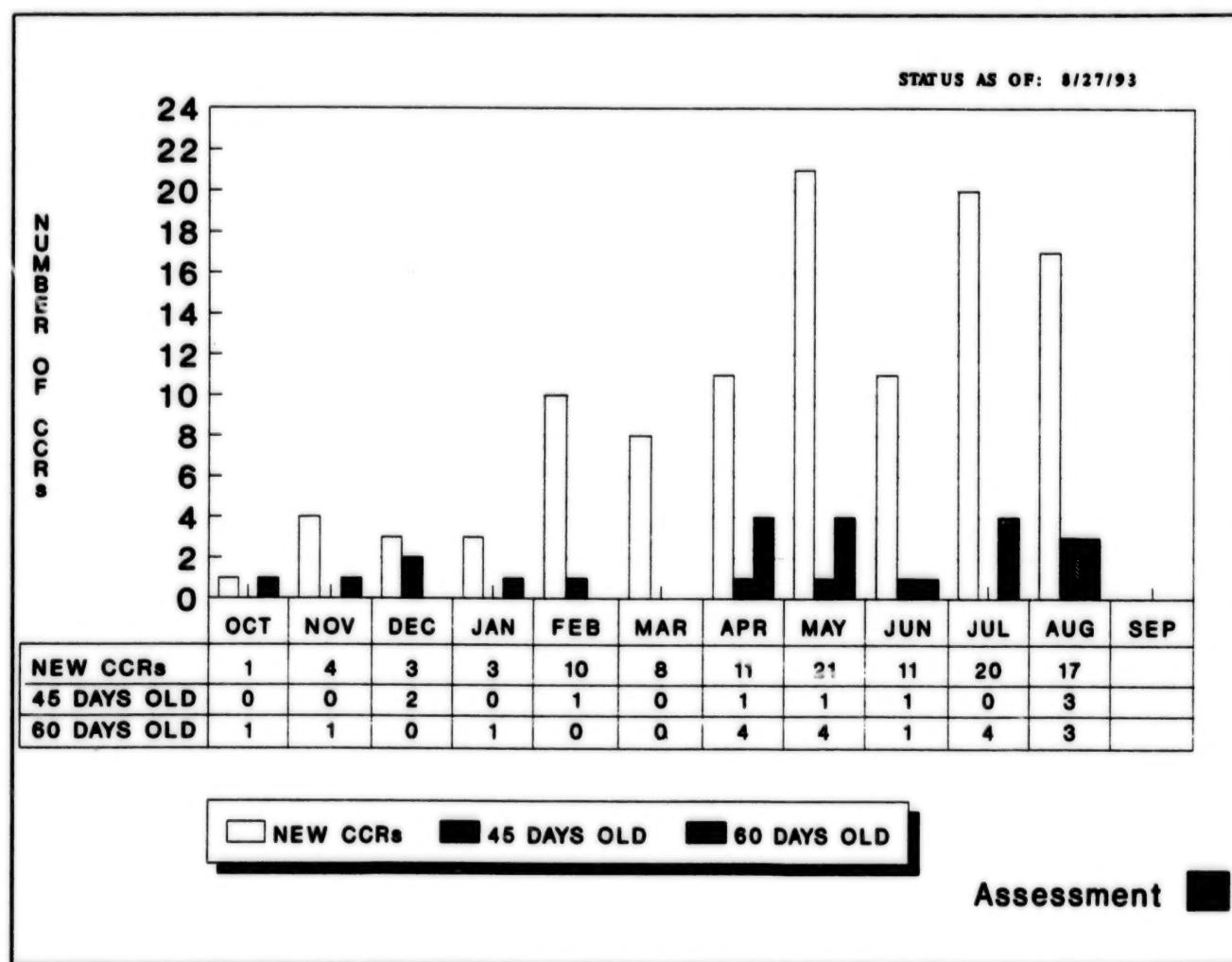


Figure 11. TRMM Project Configuration Change Requests

Log Number _____

TRMM PROJECT RISK REDUCTION PLAN

Problem Description _____ Name of Indicator _____

Originator _____ Date _____ Phone Number _____

Check the Alert Zone that applies:

Major Impact Potential Impact No Problem, but has unfavorable trend No Problem, but RRP desirable

Potential Impact: Cost Schedule Technical Performance

Describe Problem

1. Summarize problem, identify cause, quantify impact to cost, schedule, technical performance.

2. List hardware and/or software configured items affected.

Corrective Action Plan (Be specific, include dates when problem is expected to be resolved, attach separate schedule if necessary.)

Functional Manager Concurrence _____ Project Manager Concurrence _____

Figure 12. TRMM Project Risk Reduction Plan

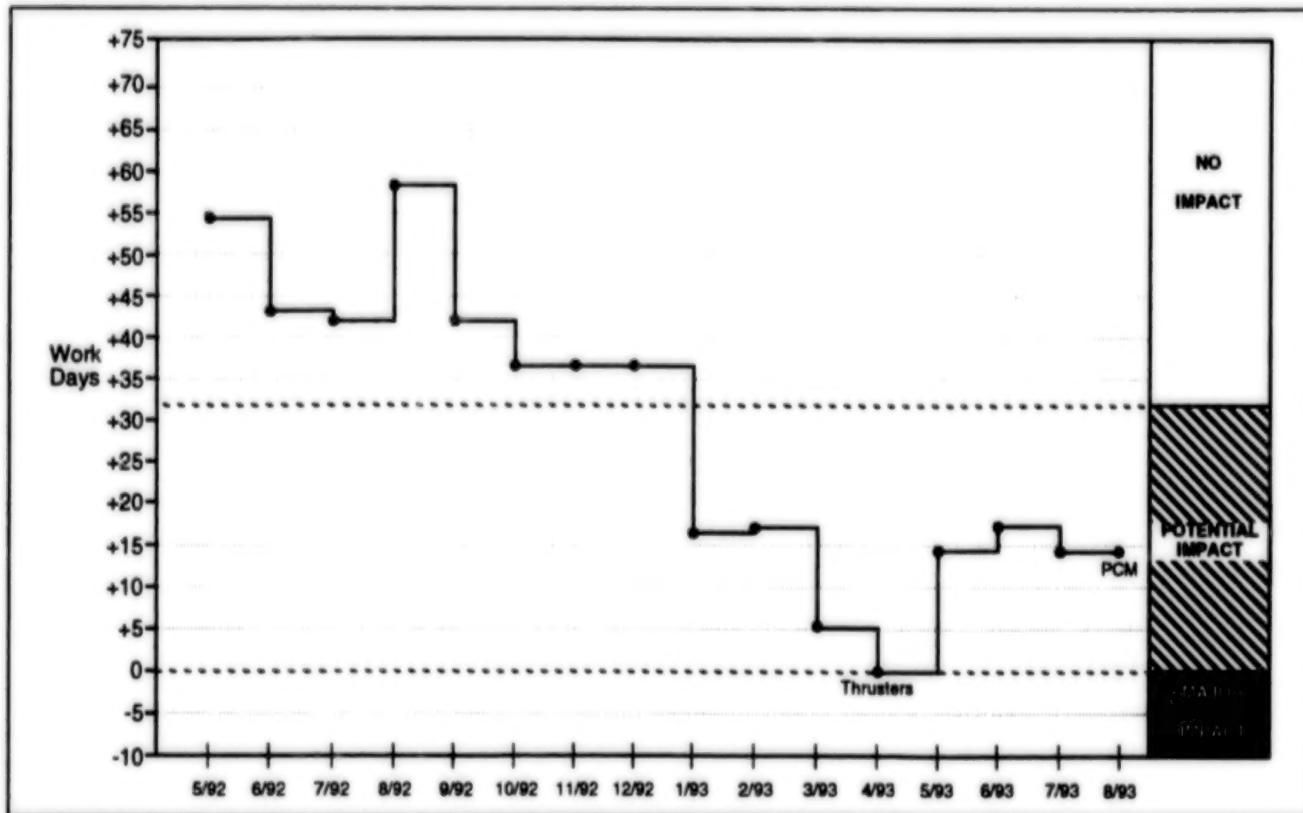


Figure 13. TRMM Reaction Control Subsystem Total Slack

Log Number	16	TRMM PROJECT RISK REDUCTION PLAN			
Problem Description	RCS - Schedule	Name of Indicator	Observatory Schedule		
Originator	Walt Majerowicz	Date	1/15/93	Phone Number	x 5622
Check the Alert Zone that applies:					
<input type="checkbox"/>	Major Impact	<input checked="" type="checkbox"/>	Potential Impact	<input type="checkbox"/>	No Problem, but has unfavorable trend
<input type="checkbox"/>	No Problem, but RRP desirable				
Potential Impact: Cost <input checked="" type="checkbox"/> Schedule <input type="checkbox"/> Technical Performance					
Describe Problem					
<ol style="list-style-type: none"> 1. Summarize problem, identify cause, quantify impact to cost, schedule technical performance. Delivery of thruster delayed due to CCR OB-0066, total slack now +17 which is in excess of Alert Zone 1. 2. List hardware and/or software configured items affected. 					
Corrective Action Plan (Be specific, include dates when problem is expected to be resolved, attach separate schedule if necessary.)					
<ol style="list-style-type: none"> 1. Release RFP by 4/2/93 need technical and schedule estimates from bidder's in order to determine if 20.5 month lead time is realistic. 2. Begin investigating work-around plan for I&T assuming thruster impact. 					
Functional Manager Concurrence			Project Manager Concurrence		

Figure 14. TRMM Project Risk Reduction Plan

In RCS, the January 1993 slack dropped to 16 days due to a technical change in the thruster configuration. Since the first risk threshold of 32 days was passed, a Risk Reduction Plan was generated (Figure 14). This problem was resolved in May 1993 by negotiating an earlier delivery with the vendor at contract award, with no additional cost. This action increased the thruster slack to 33 days. With the thruster slack no longer in an alert zone, attention was then focused on the element with the least amount of slack, the Propellant Control Module (PCM).

The risk management system has allowed the project staff to effectively use constrained resources to focus on problems which could negatively impact cost, schedule or technical objectives. Although the system requires a great deal of discipline, planning and teamwork, the ultimate result focuses the entire project team on the critical problems.

To date, the TRMM Project has succeeded in achieving its cost and schedule goals and the TRMM Project Office can provide GSFC and NASA management with highly reliable status and forecast information. The TRMM Project Office's proactive management approach focuses on prevention rather than correction. The ability to provide early warning and quick reaction analysis when changes occur has allowed the team to make informed decisions and to optimize positive results. TRMM technical, resource and management personnel clearly understand their role in aggressively managing their responsibilities. TRMM's commitment to excellence, teamwork and communication will ensure the development of a high-quality satellite, delivered on schedule and within the approved budget. This progressive management system is one of the TRMM Project's contributions to improving NASA project management effectiveness and efficiency.

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A STRATEGY OF COST CONTROL FOR MARINER VENUS/MERCURY '73

by John R. Biggs and Walter J. Downhower

The spacecraft launched by NASA on November 3, 1973 to explore Venus and Mercury proved a notable success as a development project both in space and on the ground. This article on the development points out management approaches and techniques that kept schedules and controlled costs, the intent being to stimulate thought about how to do the same with future spacecraft and payloads.

The Mariner Venus/Mercury '73 (MVM '73) project kept within its originally established goals for schedule, performance and cost. Underlying this development success was the availability of the Mariner technology. But meeting the goals demanded management determination, planning and discipline to make optimum use of state-of-the-art technology—on the part of people at NASA, JPL and The Boeing Co. (the contractor).

Pre-project Highlights

The earliest studies of the concept and scientific potential of a Venus/Mercury swing-by mission drew many to observe it could be the unique mission of the decade. It was the first to use a gravity-assist technique—taking advantage of an unusual planetary configuration existing in 1973. Using the gravitational field of Venus, it was possible to swing an Atlas-Centaur-launched spacecraft onto a flight path to Mercury. Exploration of Mercury otherwise would not have been possible without using a much larger launch vehicle.

The 1968 Planetary Exploration Summer Study conducted by the National Academy of Sciences (NAS) Space Science Board (SSB) endorsed this mission. The SSB suggested that the mission be planned around a single launch to make best use of the science funds available to NASA.

Mission Objectives

The following mission objectives, established by NASA following the Summer Study in 1968, did not change during the program's several years of design and development:

- **Primary.** During the 1973 opportunity, to conduct exploratory investigations of the planet Mercury's environment, atmosphere, surface, and body characteristics and to obtain environmental and atmospheric data from Venus during the fly-by. First priority goes to Mercury investigations.
- **Secondary.** To perform interplanetary experiments while the spacecraft flies from Earth to Mercury, and to obtain experience with a gravity-assist mission.

JPL had long experience with planetary programs, but the opportunity for other Centers to participate in the program was not foreclosed. NASA's Goddard Space Flight Center (GSFC) had plans for a Planetary Explorer spacecraft potentially able to do the mission and its approach was sufficiently attractive to invite further study. During the remainder of 1968 and 1969, both GSFC and JPL studied their respective concepts; this early competition contributed to thoroughness of the early planning effort.

The Scientists

An innovative technique was used on MVM '73 to assure early involvement of the scientific community with mission definition and preliminary design. In past missions, no effective mechanism for the early detailed planning involvement of outside scientists had evolved, and selection of principal investigators had been withheld until the completion of mission-profile studies and early sys-

tem determinations. By the time the investigators were selected in those programs, many design features had already been established.

For MVM '73, selected scientists were invited to participate in the early mission planning. A group of scientists representing the several disciplines to be involved in the science payload was selected and formed into a Science Steering Group (SSG) in September 1969. The scientists influenced the early mission and spacecraft design, holding to a minimum conflict between mission constraints and science needs.

Based on the positive results from these planning efforts, MVM '73 was presented in the FY70 NASA budget as an Office of Space Science and Applications (OSSA) "new start" at a funding level of \$3 million. An Authorization Conference Committee approved the project for inclusion in the FY70 authorization action, and funds were appropriated as requested. The scientific principal investigators were then selected in a normal fashion after project authorization.

Robert S. Kraemer, then head of planetary planning at NASA, pressed innovation in the early planning of MVM '73. Kraemer later moved to the post of planetary program director, with responsibility for implementing the project.

The "Low Cost" Attitude

The "low cost" attitude, so evident in the management of MVM '73, developed early. The study teams were instructed to consider maximum use of established designs, residual hardware and existing capabilities. Very strict financial constraints were factored into payload planning. The SSG was requested to consider minimum cost experiments that would yield acceptable scientific data. The potential experiment proposers were advised to use existing designs for science instruments, to use flight-tested experiments

wherever possible, and to consider modifications only for high-payoff options. They were also to limit quality assurance, reliability and documentation requirements to that previously applied to prior successful similar instruments. GSFC and JPL established the mission and spacecraft baseline, developed preliminary implementation plans incorporating the experiment approach being followed by the SSG, and made early cost estimates. JPL called on its extensive experience with Mariner spacecraft. Goddard proposed a spin-stabilized spacecraft of the Explorer class.

JPL proposed to commit to a fixed cost to do the MVM '73 mission in the system-contract mode. W.H. Pickering, JPL Director, advised OSSA in December 1969 that JPL could and would undertake the project for a cost not to exceed \$98 million.

The JPL Goal

After a full briefing on the approaches by GSFC and JPL (proposed science return, spacecraft configurations, management modes, manpower and cost projections), OSSA chose JPL. In a letter to Dr. Pickering, assigning project management to JPL, John E. Naugle, Associate Administrator for Space Science, made this comment regarding mission cost: "A major concern has been and remains to be the total runout cost of the project. I am sure you are aware of the cost history for which estimates have ranged from approximately \$70 million to well over \$100 million. It is mandatory that the project be accomplished for a total cost not exceeding the \$98 million quoted in your letter and strong efforts should be taken to reduce this figure." This letter set the fundamental cost understanding between OSSA and JPL.

The "Work Package" Concept

JPL expertise in conducting flight projects predominantly involved obtaining spacecraft subsystems from industry thorough the JPL technical divisions with JPL accomplishing

the spacecraft systems functions. The major challenge faced by JPL in the MVM '73 project was to utilize and adapt the fundamental JPL strengths to a system-contracting mode.

A JPL team suggested a "work package" concept as the best means to transition from the use of subsystem contractors to a systems contractor. Appropriate elements of the JPL matrix organization prepared the work packages. The project office exercised system technical direction, but the detailed definition, monitoring and control of individual work units was performed by the appropriate JPL organizational element under the overall coordination of the JPL project office.

JPL also determined other factors important to implementing the project. It selected a cost contract with award fee. A specific JPL procurement group co-located with the project office would administer the system contract and other MVM '73-related ones. It was decided that the JPL inhouse tasks should be given as much visibility and control as those of the system contractor. The constraint on resources dictated that all elements of the project, regardless of the performing organization, be monitored in the same detail, and the risks balanced across all portions of the project's activities.

PAD, Procedures and Payoff

The NASA project approval process entails a basic contract or understanding between the Administrator and the responsible Program Associate Administrator known as the *Program Authorization Document* (PAD). The initial PAD for the MVM '73 project was signed on February 27, 1970. The objectives, technical plan, major support interfaces and procurement approach discussed in that PAD remained unchanged throughout the development.

The JPL approach strongly exercised the Mariner heritage. MVM '73 benefited not only from Mariner design derivation but also

from residual hardware from past programs. The plan emphasized maximum use of existing designs, hardware and software. This approach saved perhaps 50 percent of design and development costs and perhaps 15 percent in hardware costs—a big payoff.

The Cutting Edge

The project team had lengthy discussions with JPL implementing organizations to identify the optimum way to meet cost constraints. Control of cost-at-completion became a basic concept stressed by both the JPL and Headquarters offices in an attempt to avoid the less efficient, year-by-year funding controls often followed in projects. The MVM '73 project made it clear that each assigned work unit was the total responsibility of the cognizant division and that responsibility for determining the least costly way to do the work rested squarely with the division. For each potential increase in cost, something had to be cut back. The JPL divisions almost invariably proposed specific cuts concurrent with notification to the project office of potential cost increases.

Schedule Strategy

The schedule adopted for MVM '73 provided an unusually long period for advanced planning and deferred this start of major contracts. This approach, unprecedented in launch-critical planetary programs, may have been the single most important factor in meeting cost goals.

The added risk to the mission was offset by the increase in design time and better planning of the fabrication effort. The effect was to establish a "most cost-effective" approach. The greatest number of people worked on the project for the shortest period of time. (Axiom: the shorter the schedule, the less the cost.)

Once adopted as a project philosophy, delay in implementation was applied to all aspects of the project. The systems contract was de-

layed three months beyond the schedule considered minimal by many. Other subcontract work was released on a schedule that limited the work time to a prudent minimum. A "single thread" approach was followed in the spacecraft design where options were studied, one was adopted, and the work started without carrying parallel efforts. Mission operations work was held off beyond the schedule previously considered to be optimum. Flight operations crew training was held off as long as possible. And it worked! There were no major schedule slippages, no seriously late deliveries of equipment and no extraordinary workarounds.

"Do Only the Essential"

The philosophy of "Do Only the Essential" became a discipline among project participants. To challenge the need for each operation, each added procedure, each piece of special equipment, and each separate design, redundant feature or test became routine. If a function, part, or operation was determined to be needed, then the search went on to see if hardware was available from other projects, or if the process had been developed by someone else. If the part or process was not available, then there was an attempt to use available designs.

This discipline was not only applied by the JPL managers but by Boeing as well. The Boeing spacecraft program manager proved extremely resourceful in identifying short cuts, reductions in paperwork, and unnecessary redundancy—the cost-type contract notwithstanding. The list of hardware and effort saved through this effort is too lengthy to discuss here, but the savings extended to every area of the project effort.

One unusual saving is notable. The project team encouraged a local college, assisted by several other colleges and high schools, to produce the spacecraft models, which often cost more than \$100,000. The project gained all the models required, the students and

schools gained good experience from their work on an interesting task and NASA saved dollars and encouraged local community interest and support.

Project Team

The most important ingredients to project success were the attitudes and skills of the people assigned to manage it. JPL's experience in dealing with a system contractor was limited to Surveyor, and by 1970 relatively few JPL people had been involved in the early stages of that project. The person most familiar with its operations was Walker E. "Gene" Giberson, who had been Surveyor's project manager. He was appointed MVM '73 project manager in January 1970.

Giberson assembled a small team of individuals, each selected on the basis of his past project experience and his willingness to work within firm budget allocations. The key members of this team included V. C. Clarke, Jr., mission analysis and engineering manager; J. A. Dunne, project scientist; J. R. Casani, spacecraft system manager; J. N. Wilson, assistant spacecraft system manager and N. Sirri, mission operation system manager. This team, trim in size yet representing broad experience, represented the core of MVM '73 project management.

The Guidelines

At first, the team spent considerable time developing the project's operating concepts and indoctrinating everyone involved with the organizational and project philosophy. They set and held to the following guidelines throughout the project:

- Establish early project guidelines, objectives and constraints
- Use a small staff for planning
- Prepare detailed plans and tasks before initiating a contract:
 - Specific and detailed RFPs

- A careful tradeoff assessment between JPL and contractor furnished equipment
- Use of existing documents, reports and systems
- Careful selection of fee approach
- Establish cost-at-completion planning, budgeting and emphasis
- Secure all contracts before starting work
- Keep work and budget plans up-to-date
- Exercise organizational impedance matching and communications
- Maximize technical interaction
- Use the concept of cognizant work unit engineer
- Hold frequent face-to-face meetings of operating managers
- Identify and resolve problems promptly
- Make periodic status and performance reviews
- Indoctrinate all involved with cost goals
 - Instill cost consciousness
 - Make cost goals believable
 - Develop a clear understanding of the cost-control system
- Bring manpower onto the project and move it off in a timely manner

The Hot Seat

The Headquarters Program Office/Center Project Office interface can be extremely critical to the success of a project. If the program manager and project manager have differing ambitions and objectives or, as occurred in some instances, an adversarial relationship, the project can suffer. N. William Cunningham, the Headquarters program

manager, and Gene Giberson, the JPL project manager, enjoyed an open and forthright relationship, a cornerstone of a sound management structure.

The person on the "hot seat" for cost management is, however, the project manager. The project manager is the one most responsible for establishing the attitude and the framework for the daily tradeoffs of cost, performance and schedule where it is most essential to maintain a proper perspective. Without his cost consciousness, his basic approach to costs, MVM '73 would not have enjoyed its obvious cost success. This cost attitude is the more unusual since NASA had previously stressed technical performance and schedule requirements over cost as a discipline.

The Science Steering Group selected in September 1969 held its final meeting in March 1970. In its report, the SSG recommended a minimum science payload composed of a plasma science experiment, a magnetometer, an infrared radiometer, an ultraviolet spectrometer, a television system and an energetic particles experiment.

One of the tasks of the SSG was to make a detailed cost estimate for each potential experiment—including design, development and fabrication costs of the hardware, cost of personnel support for launch and mission operations, and cost of data analysis and interpretation and publication of results. These cost estimates, plus a project estimate for integrating the instruments into the spacecraft, shaped the first science budget for the project at \$13 million.

An Announcement of Flight Opportunity (AFO) issued in March 1970 invited proposals for experiments. It stressed the intent to select only proven flight-qualified instruments. The AFO also stressed the desire to minimize documentation and stated the intent of JPL to monitor development of the instruments only at the interface level.

Forty-six proposals were received and evaluated. After ranking them in terms of science excellence, technical and engineering requirements, cost and system integration, the program office recommended seven payloads to the OSSA Associate Administrator. The payload cost estimates went as follows (in millions of dollars):

Television	\$6.226M
Radio science	0.500
Ultraviolet	0.575
Infrared	0.928
Magnetometer	0.688
Energetic particles	0.383
Plasma science	<u>0.945</u>
Total	\$10.245
Instrument integration	<u>2.355</u>
Total	\$12.600

To each of the principal investigators selected, Dr. Naugle addressed this comment: "I must emphasize, once again, that the total negotiated figure (dollar cost as selected) cannot be exceeded. Accordingly, I have instructed the JPL project office that in the event of an anticipated cost overrun, their alternatives will consist of helping you to reduce the scope of your experiment, or recommending its termination."

Science and Dollars

Whereas most past selections had been considered final at the time of announcement, the letter from Dr. Naugle clearly showed that the selection was to be considered tentative until the investigators and JPL completed negotiations. A process of fact-finding and negotiation between JPL and each of the scientific investigators followed, which resulted in well-defined relationships before the major development effort commenced.

It was made clear in the selection and negotiation process that the principal investigator was responsible for the implementation and development of the investigation, including the instrument. The project office followed

through on the intent to control principally at the instrument/spacecraft interface level. The systems contractor was responsible for integration of the instruments into the spacecraft. One innovative technique required the systems contractor to "sign off" on changes to experiment interface drawings, although the contracts for the experiments were between JPL and the investigator. This technique provided greater assurance that the systems contractor was aware of the latest configuration of the experiment hardware, and helped avoid surprises at the time of integration.

Dr. Naugle views MVM '73 as the most successful development of scientific instruments within tight cost constraints. The addition of the experiment integration costs to delivered cost brings the total for science very close to but within the original budget of \$13 million.

Meeting payload cost goals begs the question whether controls compromised the science investigations. A detailed review of the development history of each instrument clearly demonstrated that not only was there no compromise of the investigations during development, but that significant capability was added to several investigations. Any science compromise on MVM '73 reflects directly the original constraints established before experiments were selected. The decisions to tightly constrain payload costs, to fly only proven instruments and to apply go/no-go cost restrictions on instrument development are serious policy decisions to be carefully weighed. They cannot be applied to every payload but they paid off in MVM '73.

NASA and JPL held an industry briefing in February 1970 to apprise companies of the goals and constraints of the MVM '73, to provide detailed technical and program information for early planning, to encourage competition, and to enlist industry's help in determining an optimum role for a system contractor; 41 firms attended the briefing.

JPL asked the companies for suggestions regarding implementation of the systems contract approach; separate day-long meetings were held with the most interested competitors to discuss their suggestions. During these meetings, the companies made recommendations on contract scope, roles and relationships, Mariner technology transfer, contract type, GFP handling and other areas they believed were important to the effort.

A procurement plan evolved in which the systems contractor would have the major role (1) to design, fabricate, assemble, and test one flight spacecraft, one test spacecraft, associated test models, test and support equipment and appropriate spares; and (2) to provide level-of-effort support to JPL in mission analysis and engineering, JPL subsystems activities and mission operations.

RFP Features

The JPL project definition effort had been proceeding for a year at the time the Request for Proposals (RFP) was issued. The result of that effort was a very detailed RFP. It was an extensive compendium explaining project objectives, organization and implementation; schedule, control dates and documents; work breakdown structure; spacecraft design summary; scope of contract and general description of work; JPL/contractor relationships and mission operations. Its most unusual features included:

- A spacecraft systems specification which attempted to state only minimum requirements.

- The predetermined intent to divide all work into discreet work units (which allowed separation of responsibilities and facilitated work description, understanding, negotiation and JPL monitoring). The definition of each work unit was written in a standard format.
- The request for firms to propose overhead cost ceilings.
- The request for baseline and alternate cost proposals to get the best cost mix between JPL and contractor-furnished equipment.
- A call for incentive proposals which gave heavy emphasis to cost, but also stated strong preference to award fee.
- Emphasis on minimum documentation and maximum use of procedures, forms, techniques, etc. the contractor currently used.
- Detailed documentation covering Mariner '69 hardware, Mariner '71 hardware, and other JPL-furnished equipment, along with drawings, schematics, processes and procedures to assure full use of the Mariner heritage and facilitate cost estimates.

Four proposals were received. The Source Evaluation Board presentation was made to the NASA Administrator on April 28, 1971, and The Boeing Co. was selected as the systems contractor.

Category of Indirect Expense	CY 1971		CY 1972	
	Negotiated Per Contract	Actual	Negotiated Per Contract	Actual
Engineering	\$3.94	\$3.74	\$4.14	\$3.88M
Manufacturing	4.99	5.08	5.24	4.97
Productive Material	10.5%	7.9%	10.5%	6.7%
Subcontract Material	6.1%	5.5%	6.1%	3.6%
Area Administration	15.1%	14.35%	15.1%	11.9%
Group Administration (remote)	9.6%	9.75%	9.6%	7.8%

Holding Out for a Firm Negotiated Contract

The pressure to award the contract and commence work was very strong following the April selection, but the project manager and contract manager held out for a firm negotiated contract before allowing work to be started. Within six and one half weeks after selection, negotiations were completed and a definitive contract was awarded. Work started on June 17, 1971.

The cost-plus-award-fee contract emphasized the contractor's complete responsibility to meet the spacecraft system performance requirements. The effort was divided into work units, each assigned to a manager within The Boeing Co. The work units were compatible with both JPL's technical division organization and Boeing's project structure.

Controlling Overhead

A serious concern in systems contracting had been the inability to predict overhead costs. The parties agreed that a ceiling on overhead costs would be negotiated into the contract. Such ceilings on overhead are unusual in normal circumstances, and all the more so in this case, considering the depressed economic situation The Boeing Co. faced in the spring of 1971. The ceiling on overhead never was invoked because Boeing actually underran the negotiated overhead cost.

Strong cost incentives were negotiated into the contract and a process for evaluation and award emphasized performance and cost control. The award fee provisions and the system employed to carry them out appear to have been effective in contributing to the contractor's performance. Benefits included these:

- Boeing's spacecraft program manager had the opportunity to increase the fee significantly. The award fee structure allowed broad latitude in the approach to cost and performance tradeoffs.

- The process enforced periodic, results-oriented evaluations and communications at all levels. The process and the resultant dialogue tended to remove the obstacles that stand in the way of the natural motivation to do a good job. By clarifying goals, establishing emphasis, eliminating misunderstandings and highlighting problem areas for mutual attention, obstacles were removed or reduced.
- Attention of the contractor's top management was obtained by the formal feedback process (briefings supported by letters).
- The discipline of the award fee evaluation process improved JPL's internal communications at all levels, including top management on the award fee review board.

Tight Control

JPL has a reputation in the industry for aggressive contract management, often expressed as complaints of "too tight control" by subcontractors. But the JPL system proves effective in assuring performance.

In MVM '73, change orders were kept to a minimum throughout the contract and were negotiated into the contract promptly after issuance. Project office personnel monitored Boeing's work very closely. The work unit breakdown made it possible for cognizant JPL engineers to thoroughly understand the job, follow its progress in detail and identify potential problems early.

Early identification of problems coupled with open, candid discussions among The Boeing Co. and JPL managers were basic contributors to the success of the project. D.T. Gant, contracts manager, L.V. Burden, financial manager, and L.M. Bates, cost analyst, who were collocated in the project office, effectively kept the project managers alert to unexpected deviations.

The NASA Management Audit Office, not noted for its approbative descriptions of NASA operations, gave this appraisal: "In our opinion, the JPL surveillance of the contract, its assignment of capable and motivated personnel to monitor the performance of MVM '73 on a full-time basis, and the apparent stringent cost controls implemented by The Boeing Co. before contract award, and retained throughout the program, contributed to Boeing's successful cost performance under MVM '73."

Good Communications

Stressed by the managers, good communications led to early anticipation and resolution of issues and the timely availability of data for decision-making. Some of the techniques used to assure communications included:

- A weekly Agreement/Disagreement Log, maintained by work unit personnel and reviewed by the JPL spacecraft system manager and The Boeing Co. spacecraft program manager.
- Weekly face-to-face meetings between the systems contractor, systems manager and the systems contractor program manager.
- A weekly summary of agreements and formal tracking of action items.
- Daily meetings between The Boeing Co. test and operations representatives and the JPL resident staff during the system test period.
- Weekly "Problem TWX."
- Formal monthly progress reviews to give an overview and detailed status and plans with particular emphasis on problems.
- Easy access to The Boeing Co. and JPL top management (above the level of project personnel).

- Attendance at award fee briefings by Boeing's top management.
- An extensive and definitive award fee letter and briefing, held not later than 15 days after the end of each period.
- Rapid escalation of significant problems to the appropriate management level for resolution.

None of these actions should surprise good managers, but taken together, they may not be commonplace. These combined techniques greatly helped the MVM '73 project meet its goals.

Highlights of Contractor Performance

The Boeing Co. faced an uncertain general business position at the time the MVM '73 project contract was issued. Major reductions had been made in Boeing's commercial airplane operations, and significant reductions in employment had been made at Boeing Aerospace Co.

Despite the drastic reduction in backlog and direct workload, Boeing was able to reduce overhead costs and even underrun the overhead projections on the MVM '73. The aerospace industry and its government customers are conditioned to the increase of overhead runs when the direct base decreases. This "fact" is considered by many to be axiomatic and inviolate; overhead costs are regarded as "fixed" or unalterable and necessary to support the base for doing business. The example of Boeing's experience in 1970 and 1971 could be a good case study in ways to reduce overhead expense as the direct base decreases.

E. G. Czarnecki served as The Boeing Co. MVM spacecraft program manager from the early proposal phases in 1970 through early 1973. H. Kennet served as deputy program manager and succeeded Czarnecki. Their

participation contributed immensely to the success of MVM '73. They have reviewed their experience, and underscored these management concepts and techniques employed on MVM '73:

- Spacecraft requirements must be defined clearly and early.
- Match people (skills) to work unit tasks.
- Use the "cognizant work unit engineer" concept.
- Select the baseline configuration early.
- Implement a system of program reviews and reporting with joint chairmanship by contractor and customer.
- Define and assess technical performance, schedule and cost risks and develop work-around plans.
- Educate key personnel in the company's cost accounting system so that when tradeoffs and decisions are to be made, all factors are properly considered and their true impact on cost understood.
- Shorten and improve communications through collocation and program organization.
- Establish organizational relationships (e.g., JPL/Boeing) and communication channels early.
- Motivate people through performance assessment, promotion, compensation and achievement awards.
- Emphasize cost trades during design.
- Ensure that only essential work is accomplished.
- Use an objective performance measurement system.
- Rely on each cognizant work unit engineer for early identification, reporting and, when feasible, problem resolution.
- Use dedicated manufacturing and test facilities.
- On-load and off-load manpower in a timely fashion.
- Use recovery ("tiger") teams to work problems. Teams of specialists from outside the program can be assigned problems and provide instant expertise without a continued expense to the program.

A Postscript

The MVM '73 spacecraft (Mariner 10) was launched on November 3, 1973. A number of problems developed early in the flight, but none degraded the mission and none was the obvious result of actions taken to control cost. The spacecraft reached Venus on February 5, 1974, and returned a full set of scientific data, including more than 4,000 pictures. The gravitational attraction of Venus altered the spacecraft's flight path as planned, swinging it toward Mercury. The spacecraft passed within 500 miles of Mercury's surface on March 29, 1974, and returned the first close scientific observations and pictures of the planet. The project is currently [1974] anticipating a modest underrun at completion. So MVM '73 more than met its original performance objectives and, in addition, served to work out management approaches and techniques to control costs.

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PERFORMANCE MEASUREMENT: A TOOL FOR PROGRAM CONTROL

by Nancy Abell

The NASA program and project managers of the 1990s will continue to work in the environment of constrained resources in terms of reduced budgets, limited staffing and tight schedules. In a speech to the Explorers Club in January 1989, former NASA Administrator James Fletcher stated:

The funds being requested do not permit us the luxury of backups, of alternatives, of programmatic robustness. Virtually every element of the program is being pursued on a success schedule—and we know in advance that there will be unforeseen technical problems to solve and dilemmas to face which will require internal adjustments and constraints.

In this environment there are focused efforts to improve program and project management. One potentially powerful tool available to the project manager which has been used successfully in many government agencies is performance measurement.

Performance measurement is a management tool for planning, monitoring and controlling all aspects of program and project management—cost, schedule and technical requirements. It is a means (concept and approach) to a desired end (effective program planning and control). To reach the desired end, however, performance measurement must be applied and used appropriately, with full knowledge and recognition of its power and of its limitations—what it can and cannot do for the project manager.

Performance measurement is not a new concept to the government or to the aerospace industry. It has its origins in the Department of Defense (DoD) programs of the 1960s. Interest and application of the performance measurement concept spread to other gov-

ernment agencies in the 1970s and 1980s. Today performance measurement is being applied to major programs of the DoD, National Security Agency, Department of Energy, Federal Aviation Administration and NASA. Performance measurement is widely endorsed as a valid approach to controlling contract performance.

The Goddard Space Flight Center (GSFC) has been implementing performance measurement system (PMS) requirements since 1983 on major research and development (R&D) contracts with a price of \$25 million or more and a period of performance longer than one year. GSFC's PMS policy was established by the Center Director to provide for consistent application on all major Center acquisitions. Use of performance measurement is also encouraged on R&D contracts in the \$10-25 million range, but applied on a case-by-case basis. GSFC currently has 12 contracts in various project phases that have PMS requirements. With the large number of major independent spacecraft and instrument development contracts at GSFC, such as the various meteorological spacecraft and instruments of the Geostationary Operational Environmental Satellite and Television and Infrared Observational Satellite programs, we have had the opportunity to continually improve our implementation of PMS through a "lessons learned" approach. Some of the more effective PMS applications have been on the Gamma Ray Observatory and the Tracking and Data Relay Satellite System spacecraft contracts.

What is the potential of this management tool? What does performance measurement do that a traditional plan vs. actual technique cannot do? Performance measurement provides an improvement over the customary comparison of how much money was spent

(actual cost) vs. how much was planned to be spent based on a schedule of activities (work planned). This commonly used plan vs. actual comparison does not allow one to know from the numerical data if the actual cost incurred was for work intended to be done.

With performance measurement, actual work progress (work done, also known as earned value) is quantified by an objective measure of how much work has been accomplished on the program. This added dimension of a quantitative assessment of work accomplished allows for comparisons to be made between the value of work that was done vs. the work that was planned to be done (schedule variance). It also allows for a comparison of the actual cost of work that was done vs. the planned value of the work that was done (cost variance). This analysis then provides for early identification and quantification of cost and schedule problems. A graphic depiction of the data available from the traditional plan vs. actual tech-

nique compared to those available from a performance measurement system may serve to more clearly illustrate the concept. A hypothetical spacecraft program is expected to take five years to build at a cost of \$500 million. Figure 1 shows the traditional plan vs. actual technique. If "time now" is the completion of year 2, the graph indicates that we had planned to spend \$250 million. The actual cost (i.e., time card charges, material expenses, etc.) reported to the government is \$200 million.

What can a project manager conclude from this information? Is it possible to determine if this program is overrunning or underrunning? With this limited information available, a project manager may assume that the contract is underrunning and would have no basis to question the assumption that this program will underrun at completion. At a minimum it currently appears that the \$500 million funding estimate is adequate to complete this effort.

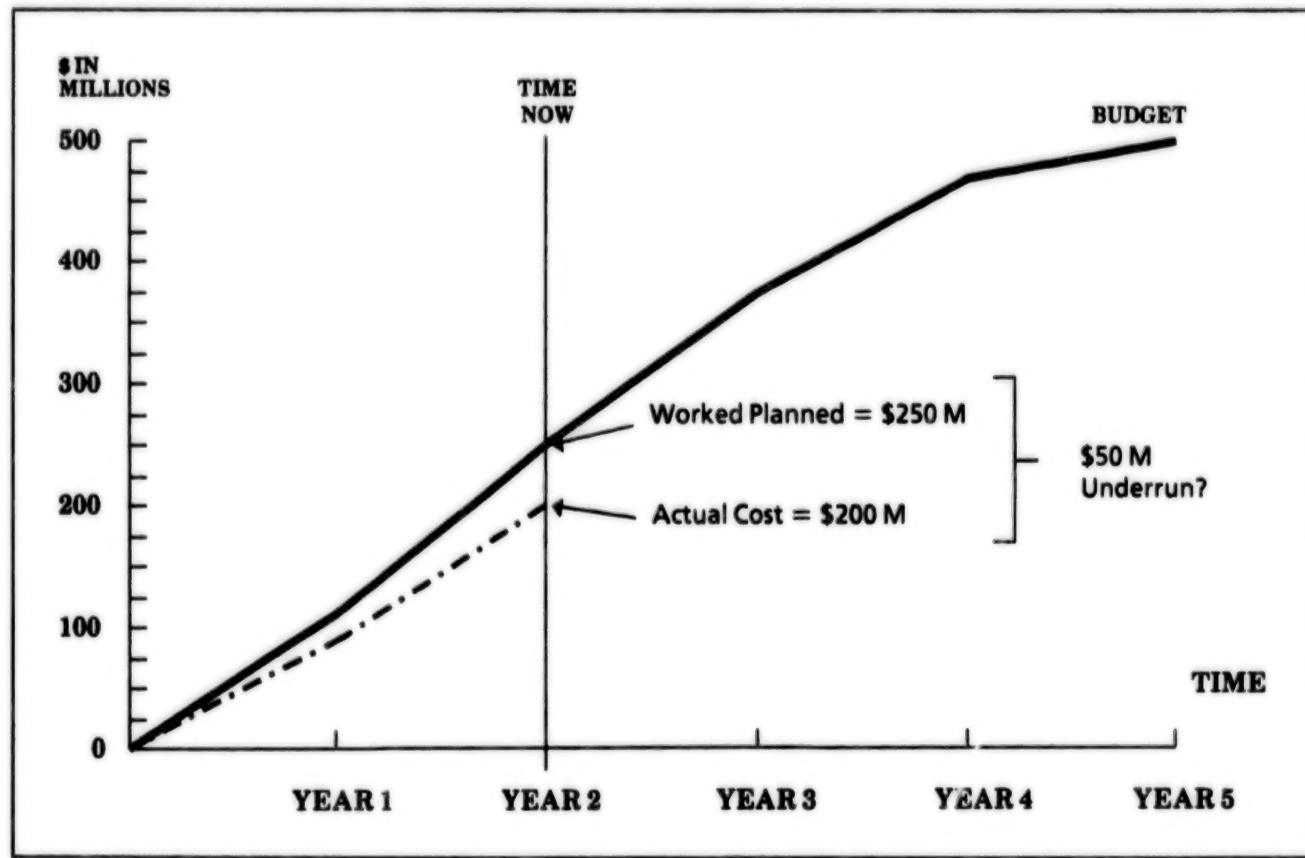


Figure 1. Traditional Plan vs. Actual Technique

In Figure 2 an additional data point has been added to the same hypothetical spacecraft program. The contractor has assessed the value of the work accomplished (or earned value) to date. This new information reveals that of the \$250 million of work planned to be done to date, only \$150 million has been done. Some work that was planned to be done has not been done and is reflected as a \$100 million schedule variance. Also, the \$150 million worth of work done can be compared with the actual cost of \$200 million.

This comparison shows the planned value of the work vs. the actual cost of that same piece of work. Now the project manager can see that this program is actually overrunning by \$50 million to date. We now have enough data to question the validity of the \$500 million funding estimate for completion of this effort. We can begin to see that this program is headed for an overrun of costs at

completion along with potential schedule slippage.

As a result, the project manager having the PMS data available in Figure 2 is better able to estimate early the total costs and projected period of performance of this program, therefore avoiding a surprise overrun much later in the program. If the data yield a "doom and gloom" assessment, there is opportunity to make decisions early to avoid an approach that is too costly or that takes too long. The basic objective of performance measurement systems is to provide a suitable basis for responsible decision-making by both the contractor and the government management by ensuring that (1) the contractor is using effective internal cost and schedule management control systems, and (2) the government can rely on valid, timely and auditable data to be produced by those systems to determine program status.

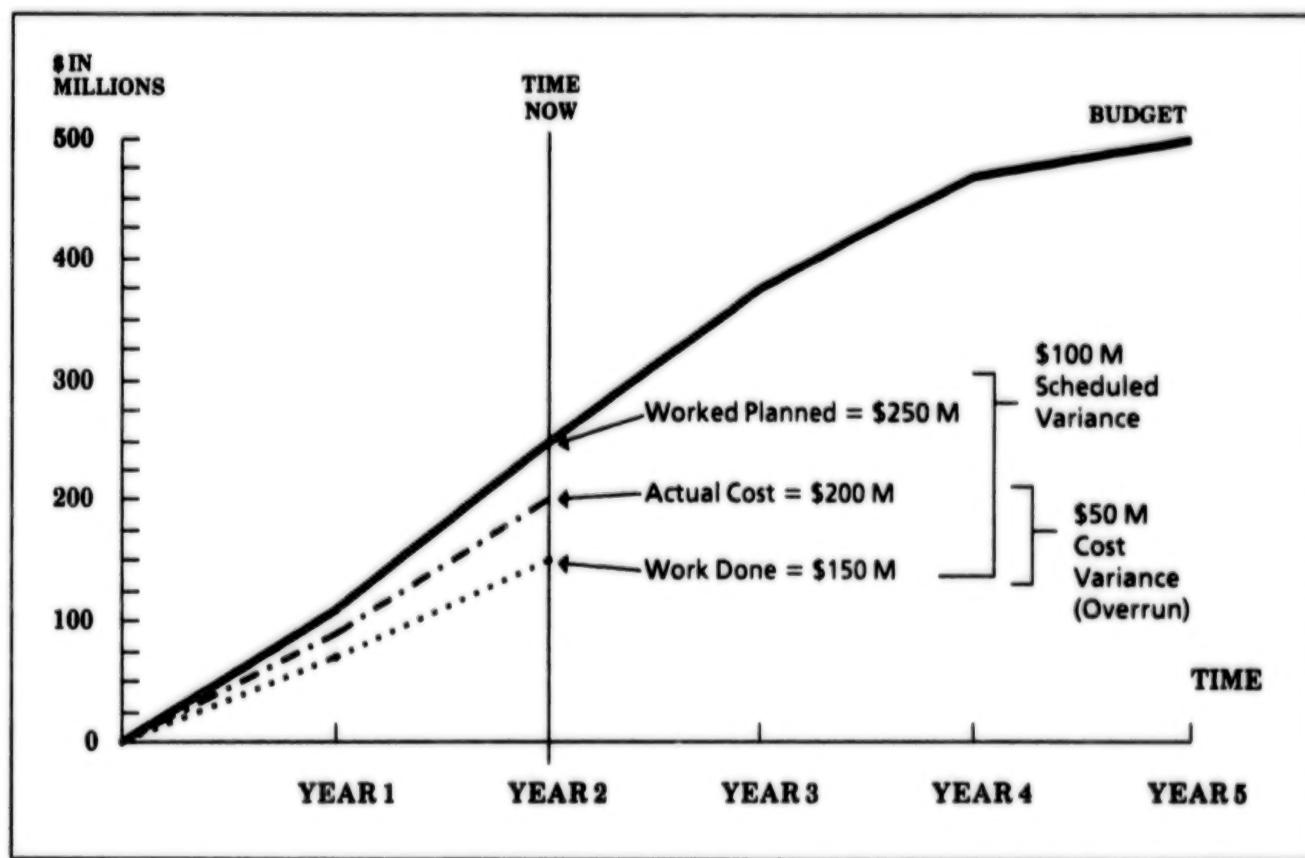


Figure 2. Performance Measurement Technique

Unfortunately, there has not been a consistent experience within the Agency regarding PMS implementation. Personnel at various NASA Centers and in the aerospace industry believe that while some NASA applications of PMS have been successful and effective, other attempts to use PMS as a management tool have actually been counterproductive. In some instances, performance measurement systems have not always provided accurate reporting of cost and schedule status, and there are differing opinions about why PMS did not work in these instances. The most prevalent of these is that in the NASA environment and culture, a disciplined approach to program management is not appropriate or applicable.

While it is healthy to question the worth and applicability of PMS for NASA programs, it is also beneficial to explore some of the common sense features of PMS that have proven effective in controlling project costs and schedules in many government agencies for the past 22 years.

Some Basic Principles

Performance measurement can work for you if you apply some basic principles.

- *Plan the entire contractual effort.* It is essential to plan the work for the entire period of performance. Near-term work is planned in detail while future work can be planned at a summary level. Failure to recognize all of the work to be done makes it impossible to properly allocate resources. Programs could consume too many of the resources on the near-term work and not leave enough to do the work downstream.
- *Maintain baseline integrity.* The measurement of actual conditions against a disciplined or controlled plan reveals performance trends that can help to predict future conditions and to determine a future course of action.

- *Determine accomplishment at the level at which the work is performed.* Who can better assess the work that has been done and the work remaining to be done than the manager responsible for performing the work?
- *Measure accomplishment objectively.* The most valuable status assessment of a piece of work is based on pre-defined milestones as opposed to personal feelings and prejudices lacking reality or substance.
- *Summarize for higher levels of management.* While accomplishment is assessed at a relatively low level, summary reporting to higher levels of management, where resources are made available, is also essential for control.
- *Analyze variances and forecast impact.* Variances are simply indications that actual conditions are different from the original assumptions, and variances may indicate the existence of current or potential problems. Analysis of the variances allows management to correct problems or to redirect efforts to avoid potential problems, as well as to project cost at completion.

In summary, the concept of performance measurement is good, common sense program management that NASA project managers have always practiced, but perhaps not in a formal way.

Specifying Customer Requirements

NASA authority for performance measurement is based on the agency requirement specified in NASA Management Instruction 9501.1 "NASA Contractor Financial Management Reporting System" and NASA Handbook 9501.2B *Procedures for Contractor Reporting of Correlated Cost and Performance Data*. The NASA Form 533P (where "P" represents performance) has been used

by contractors to report performance data to NASA, unless the contractor has another format that serves as the equivalent. The 533P is essentially a minimum NASA requirement for data reporting purposes only. It does not require that an identifiable system or set of subsystems support the data. As the contractors are free to generate data in any way they desire, there is the high potential for invalid or misleading data if this is the only requirement placed on a contractor related to performance measurement. Without a system requirement for visibility and control of the baseline, for objectivity in measuring accomplishment, or for discipline in forecasting estimates to completion, performance measurement may not yield valuable information. While data can be reported on a 533P, a more disciplined approach to the management system is needed to identify some rules for performance measurement systems. These rules are known within the government and aerospace industry as the "criteria."

The performance measurement criteria do not identify a specific management control system to be applied to a program; rather, they represent a set of standards against which to measure the acceptability of a contractor's cost and schedule control system. There is, in fact, a variety of equally effective ways for contractors to meet the criteria requirements. The criteria allow a company to organize in any way that suits the company's philosophy and style. The criteria also allow a company to develop any desired policies, procedures or methods that meet the requirements. The criteria address the age-old questions of any project manager: What work is to be done? Who will do it? When is it going to be done? How much will it cost? Where is the program heading? What has changed?

The contractors address these questions through their management systems' integrated set of subsystems. These are subsystems that would be required to manage a pro-

gram whether or not a performance measurement requirement was imposed. Performance measurement criteria simply require that a more disciplined approach be applied to each subsystem. The PMS subsystems are (1) work authorization, (2) budgeting, (3) scheduling, (4) data accumulation, (5) variance analysis and estimate at completion, (6) subcontract and material control and accountability, (7) indirect expense management, and (8) change baseline control. PMS, then, does not address just the accounting system, but rather it addresses the integrated set of subsystems that constitute all elements of program planning and control.

A Good Management System

The key to the power of performance measurement is that performance measurement data are only as valid as the management system that provides them. If a contractor operates a sound internal management system, the customer should be able to extract summary data from that system that reflect project status. To have a valid management system applied to NASA work in contractor plants, several conditions need to be met.

First, a *management commitment* from the top down is required—all levels of management support are essential. It is not enough to have project financial or resources support personnel discussing PMS with the contractor. The involvement of technical personnel is critical. PMS involves all aspects of program management and needs to be viewed in this way by NASA project and functional management personnel to be effective.

Second, management system *discipline* must be stressed and required. While it may be desirable to maintain a spirit of cooperation and non-adversarial relations with our contractors, PMS is not of any value without a disciplined approach to management. Without a requirement for the contractor to maintain a baseline, to apply objective techniques for performance measurement, or to reliably

forecast the cost to completion, there can be no confidence in the value of the data that the management system generates and that the contractor reports to NASA on a monthly basis.

Third, use of *data generated by the PMS* is essential. A few simple mathematical formulas and computations yield very revealing information about the project status and potential future of the program. Use of data serves to facilitate communications internally and between NASA and the contractor.

Fourth, *corrective action* needs to be taken when problems are identified. A management system supplies data points, not solutions. It provides visibility into cost, schedule and technical status. A system, however, does not manage the project, people do. A system cannot eliminate schedule slippages or stop overruns, but it can help the project manager to understand the potential impact if trends are allowed to continue without mid-course correction.

Fifth, an *in-plant review* of the contractor's management system applied to a program and conducted by a NASA team of interested and knowledgeable technical and resources personnel is critical. The NASA personnel gain invaluable knowledge of the policies, methods and procedures used by the contractor to generate monthly status reports. By understanding the source of the data, we can calibrate the validity of our monthly customer reports and require the contractor to revise procedures that do not produce valid data.

PMS is not intended to replace traditional management tools—it should enhance them. Day-to-day program management is essential. In fact, if managers are relying solely on performance measurement data generated at month-end, they will be learning of problem situations much too late to be effective. Periodic status reviews, "kicking the tires," and

routine communication internal to the contractor and between the contractor and government managers are critical in managing a program. PMS may identify a new problem, but in most cases, it allows quantification of a known problem through all elements of the work breakdown structure and through the functional organizations to provide a basis for improved management decisions.

Cost Effectiveness

In times of constrained resources it is reasonable for managers to question the cost effectiveness of PMS. What are the benefits and associated costs? The question is difficult to answer, however, since both the benefits and costs are nearly impossible to quantify.

PMS results in a better controlled project with improved communication, both internally and with the customer. To quantify the benefits is to ask, "What is the value of good management?" It is not evident how a cost savings (or cost avoidance), a shortened schedule, or improved technical performance through corrective action can be clearly associated with results or a specific cost.

The costs of PMS have also defied quantification for 22 years. The PMS-unique costs on the total contract cannot be separately identified from the management costs that would be incurred in any case. They are not routinely collected by contractors, nor is it considered practical to do so. This was illustrated in a 1987 survey of GSFC contractors who had implemented a PMS requirement. In the survey, some contractors suggested that the costs of PMS beyond the usual management costs may be expressed as a percentage ranging from 2 percent to 6 percent of total contract costs. In each case, however, the contractor could not substantiate the percentage. It was someone's "non-scientific estimate," as stated by one contractor. Surveys conducted by the DoD show that there is no correlation between the cost of PMS and the contract costs.

This is not to say that there cannot be costs associated with PMS requirements. In fact, the cost of implementing PMS is in direct proportion to the quality of the existing management system. The poorer the state of the contractor's system, the greater the need for improvement and the more it will cost to improve. Contractors who maintain discipline in their systems would incur very low costs to implement PMS on subsequent contracts. If the same contractors did not maintain their systems, over time the cost to implement PMS on future contracts would be greater as the need for improvement became greater.

Further, if there is not an existing integrated cost and schedule management system, the contractor will certainly incur costs to develop one. GSFC experience, however, has been that contractors awarded major development procurements that contain PMS requirements are contractors who already have operational PMS systems as a result of their dealings with DoD. Costs of PMS have been minimal compared to the significantly greater value added.

There is one additional factor to consider in a discussion of the costs of PMS. Typical points of contention between the government and industry concerning PMS implementation include the levels of detail identified for management and reporting, and the variance analysis thresholds identified for customer reporting. It is possible to avoid incurring unnecessary cost to the government and frustration for the contractor by not requesting reports that no one reads or uses, or "nice to have" items or analyses.

In summary, with the focus on efforts to improve program and project management, PMS is a potentially valuable tool. Like any tool, however, it is only as valuable as the user chooses to make it. Implemented properly, PMS can ensure the generation of valid cost and schedule performance data to ease the manager's decision-making process, which can result in more effective program planning and control.

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UNCLAS

PROGRAM CONTROL FOR MISSION SUCCESS

by G. W. Longanecker

My first premise is that in order to exercise program control, you must have a controllable program, which is one that has been properly scoped technically, realistically scheduled, and adequately budgeted.

The first step in scoping a program is obtaining a set of minimum performance requirements to meet the mission objectives. I know that this is a difficult task, because your customer is intent on achieving the maximum possible performance. However, my recommendation is to get an agreement with your customer on the minimum requirements, and then set the specifications to achieve a reasonably increased level of performance. This will allow for possible descoping actions later in the program, should the need arise. Since our programs nearly always involve state-of-the-art technology, and with today's emphasis on resource control, a good descoping plan developed early in the program is important to have in your back pocket.

The other two ingredients of a controllable program are schedule and cost. The two are very much interdependent and must be balanced with the degree of risk deemed appropriate for the program. There has been a lot of rhetoric on the subject of risk, especially in recent years. However, in my 30 years with the agency, I really didn't see much risk-taking, even with the unmanned scientific and applications satellite programs. Risk is extremely difficult to quantify, especially when you're dealing with single satellite programs. How do you explain a risk trade-off to a group of space physicists who are committing possibly half of their professional careers to a single satellite mission?

My consummate goal was always mission success. What this really boils down to is that you need to have adequate schedule slack

and budget contingency to solve the inevitable problems that will confront you along the way. Headquarters must hold sufficient reserves to cover any changes in scope. This is important enough to reiterate. The project manager at the field Center budgets and controls reserves for problem solving; the program manager at Headquarters budgets and controls reserves for scope changes. The last line of defense is to descope the program.

As I said earlier, if you have set your specifications with some margin over the minimum goals, you should have some room to descope and still meet mission objectives. The real challenge for a manager is that you probably will have to make some descoping decisions during the development phase so that you have some remaining contingency for the test and evaluation phase, mission operations, data collection and data processing.

Properly scoping a program requires that sufficient studies be performed during the definition phase. As a rule of thumb, four to eight percent of the expected total run-out cost of a program should be spent through Phase B. In my experience, NASA is notorious for skimping on definition-phase funding. When you skimp during Phase A and Phase B, you have an open invitation to performance, schedule and budget problems during Phases C and D. As part of the procurement planning process, you will develop in-house a "should-cost" estimate for the program. Your budget requests will be based on this "should-cost" figure plus contingency. Because of competition, you will most likely negotiate a contract for less than the "should-cost" estimate. The difference should not be considered part of your contingency for problem solving, but rather it represents the additional funds required to realistically perform the prescribed effort without prob-

lems. Occasionally a contractor will propose a scheme that should save some money, but again my experience has been that you should pay attention to your "should-cost" estimate.

Beyond the programmatic obstacles to a controllable program, the single biggest hardware obstacle in my experience has been piece parts. I can't remember a single program (and I've launched 21 satellites) where we didn't have problems with piece parts. We'd design a circuit, breadboard it, test it and then find that we couldn't get flight-qualified versions of the parts. We also suffered from being a small-volume user of piece parts since most of our programs involved a single satellite. The only advice I can offer is to use standard parts as much as possible in your designs, order your parts as early as possible in the program, and look for second-source suppliers for your critical parts. Even after doing all of the above, the odds are that you will have piece part delivery problems.

As for program control, there are many good techniques and tools. Everything starts with a good work breakdown structure (WBS). You will have developed one during the definition phase and for the Phase C and D procurement package and, subsequent to contract award, will agree to the WBS with your prime contractor. The WBS is the basis for your schedule projection and budget estimate. It must have sufficient granularity to identify the critical elements or building blocks of the program.

Your schedule must have slack identified at critical points in the program. It is not sufficient to carry all the slack in the period just before the launch readiness date. This is especially true when you're dealing with inter-governmental or international partners in a cooperative program. In most cases you'll find that the cooperating agencies have even less flexibility to deal with schedule and budget changes than we do in NASA. Once es-

tablished, the schedules can be tracked by any number of computer-generated systems. Critical paths are easily identified and tracked. However, I advise you not to rely solely on the automated schedule systems. I've always found it useful to prepare a few charts on critical elements that I could update manually to look for schedule trends. My favorite is one that tracked on a monthly basis, for a few selected milestones, the currently planned date versus the originally scheduled date (Figure 1).

I would frequently find that I could apply the slope of the trend for intermediate milestones to forecast the most probable completion date for a downstream event, even though the contractor continued to forecast the original event date. I found it easier to look at my few graphs than to study the computer-generated charts covering the walls of the "war room." You have to keep a perspective on the big picture.

The final element of program control that I wish to discuss is a performance measurement system (PMS), or earned value system, which allows you to track progress versus expended resources compared to your plan. Essentially all major contractors have a PMS that they use for their programs. The key word here is "use." Having a PMS in your contract is a useless exercise if the contractor is not actually using the system to help manage the program. Accordingly, you should adopt the system your contractor is familiar with, rather than insist on a similar but different system. Due to the nature of our business, changes to the program baseline are to be expected. Obviously, such changes should be kept to the absolute minimum, but when it's unavoidable, any significant change must be quickly incorporated into the PMS.

Reporting earned value against an outdated plan is useless at best. It can be worse than useless if someone believes data that is blindly cranked out, based on an outdated plan. If

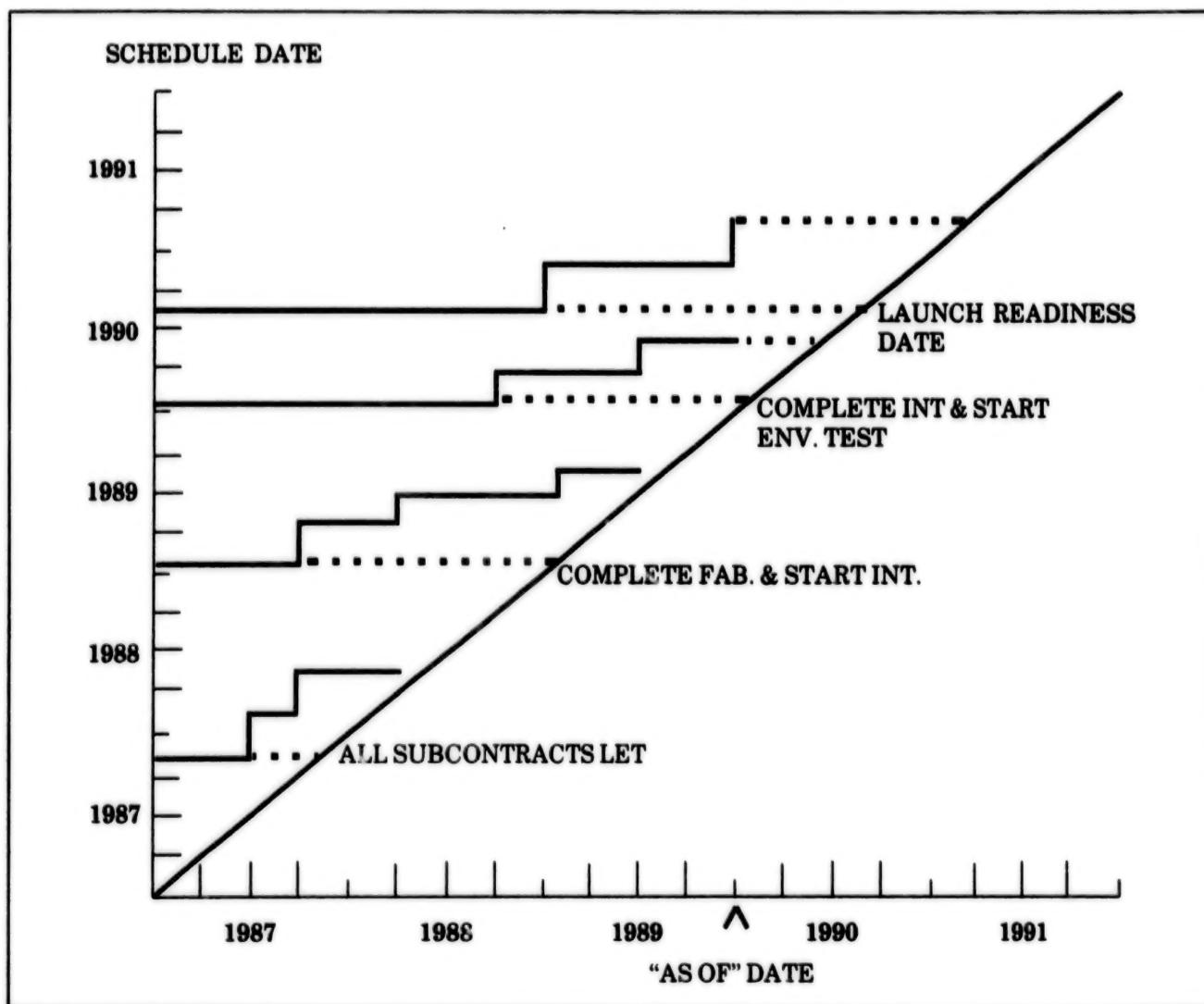


Figure 1. Sample Trend Chart

the data is current, a PMS can help you detect the trouble spots sooner and, therefore, direct your problem-solving energies more efficiently.

As with automated scheduling systems, PMS is not a panacea for the managers. You have to keep track of the big picture, and above all, use good old common sense.

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UNCLAS

THE MSFC PROGRAM CONTROL DEVELOPMENT PROGRAM

It is the policy of the Marshall Space Flight Center (MSFC) that employees be given the opportunity to develop their individual skills and realize their full potential consistent with their selected career path and with the overall Center's needs and objectives.

The MSFC Program Control Development Program has been designed to assist individuals who have selected Program Control (Figure 1) or Program Analyst Program Control (Figure 2) as a career path to achieve their ultimate career goals. Individuals selected to participate in the MSFC Program Control Development Program will be provided with development training in the various Program Control functional areas identified in the NASA Program Control Model (Figure 3).

The MSFC Program Control Development Program should be mutually beneficial to the individual and to MSFC. Each individual will be afforded the opportunity for pursuing his or her career goals while simultaneously providing the Center with a source of knowledgeable and well-trained people for strategic positions within the Program Control discipline. The purpose of the MSFC Program Control Development Program is to develop individual skills in the various Program Control functions by on-the-job and classroom instructional training on the various systems, tools, techniques and processes utilized in these areas.

The Program offers a systematic approach for individual development by:

- Allowing for rotational job assignments to obtain on-the-job training in the various Program Control functional areas.

- Providing classroom instructional training on various program control systems, processes and procedures to assist in the development of skills required for the Program Control functional areas.
- Encouraging continuation of the individual's formal education as a means of self-improvement.

The MSFC Program Control Development Program is made available to individuals in the AST classification, as well as individuals in the Program Analyst classification who have selected Program Control as a career path, and who have been selected for participation in this program. Applicants may be nominated by the organizations or self-nominated.

Selection Process

A committee is appointed by the administrative Operations Office to review and select applications for the MSFC Program Control Development Program. The committee is comprised of membership from the Administrative Operations office, Comptroller's office and the Program or Project Office.

The means to be used for publicizing vacancies for this program may be reassignment announcements, *The Personnel Perspective*, *The Marshall Star* or other media. The opportunities will open to GS-11, -12 and -13 AST applicants, with potential progression to the GS-13 level, if selection was at a lower level, based upon successful completion of the program. They will open to GS-11 and GS-12 Program Analyst applicants, with potential progression to the GS-12 level, if selection was at a lower level, based upon successful completion of the program.

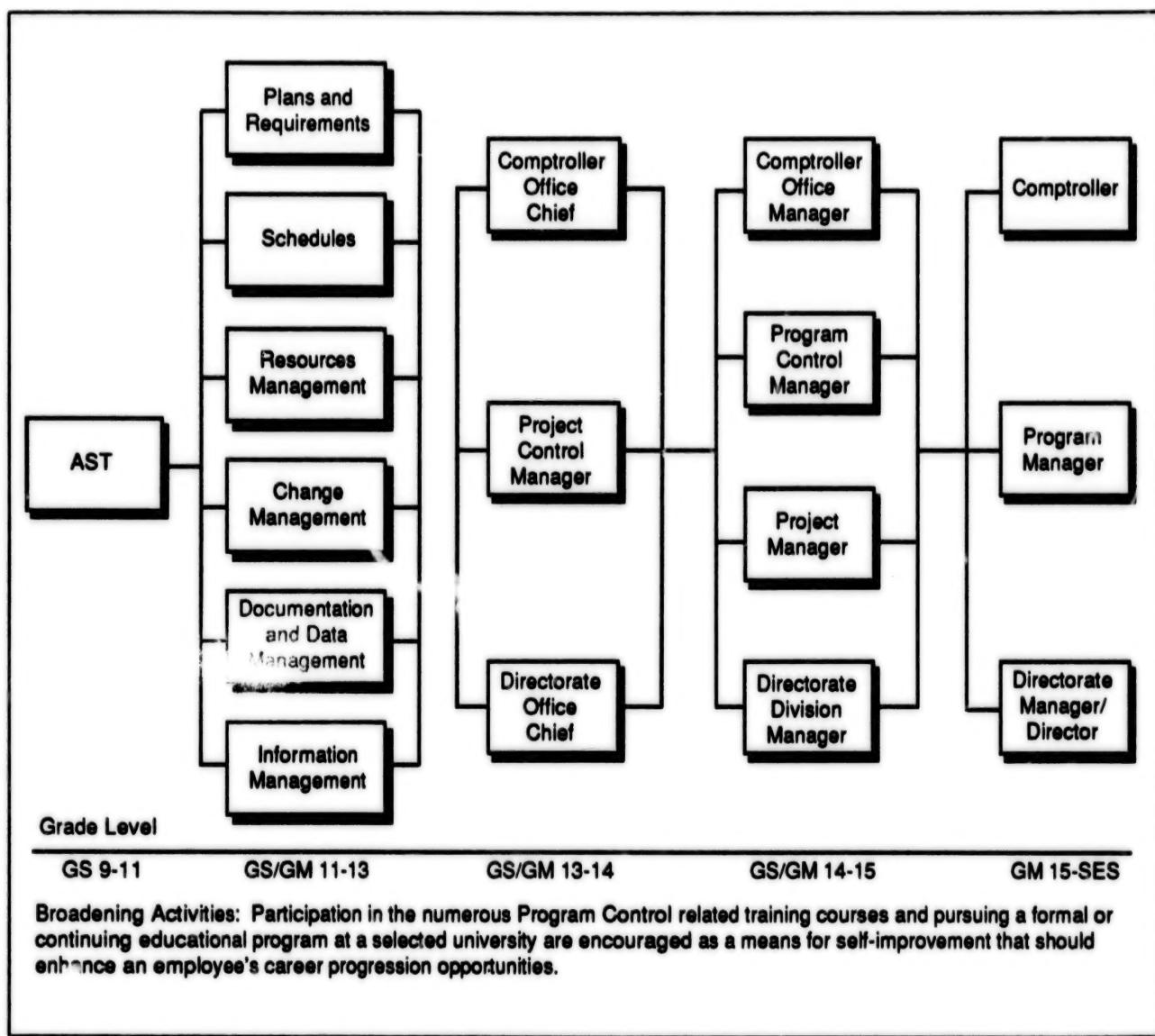


Figure 1. Example of AST Program Control Career Progression

Selection is based on the individual's application and personal interviews. Notification of selection and final appointment to the program will be made by the Administrative Operations Office, following a review by the Director of Administrative Operations and the Comptroller.

Individuals selected for this program are assigned to the MSFC Comptroller's Office for a two-year developmental period. During this period, individuals will be temporarily assigned on a rotational basis to offices identified for specific on-the-job training for the indicated periods. To the extent possible, re-

lated classroom instructional training for all Program Control functional areas will be offered during this two-year period.

Standard Individual Development Plans will be prepared for each individual to schedule:

- Rotational assignments, in order to minimize any impact on the organization providing the training.
- Classroom instructional training courses identified in this program, as well as other pertinent courses that might become available.

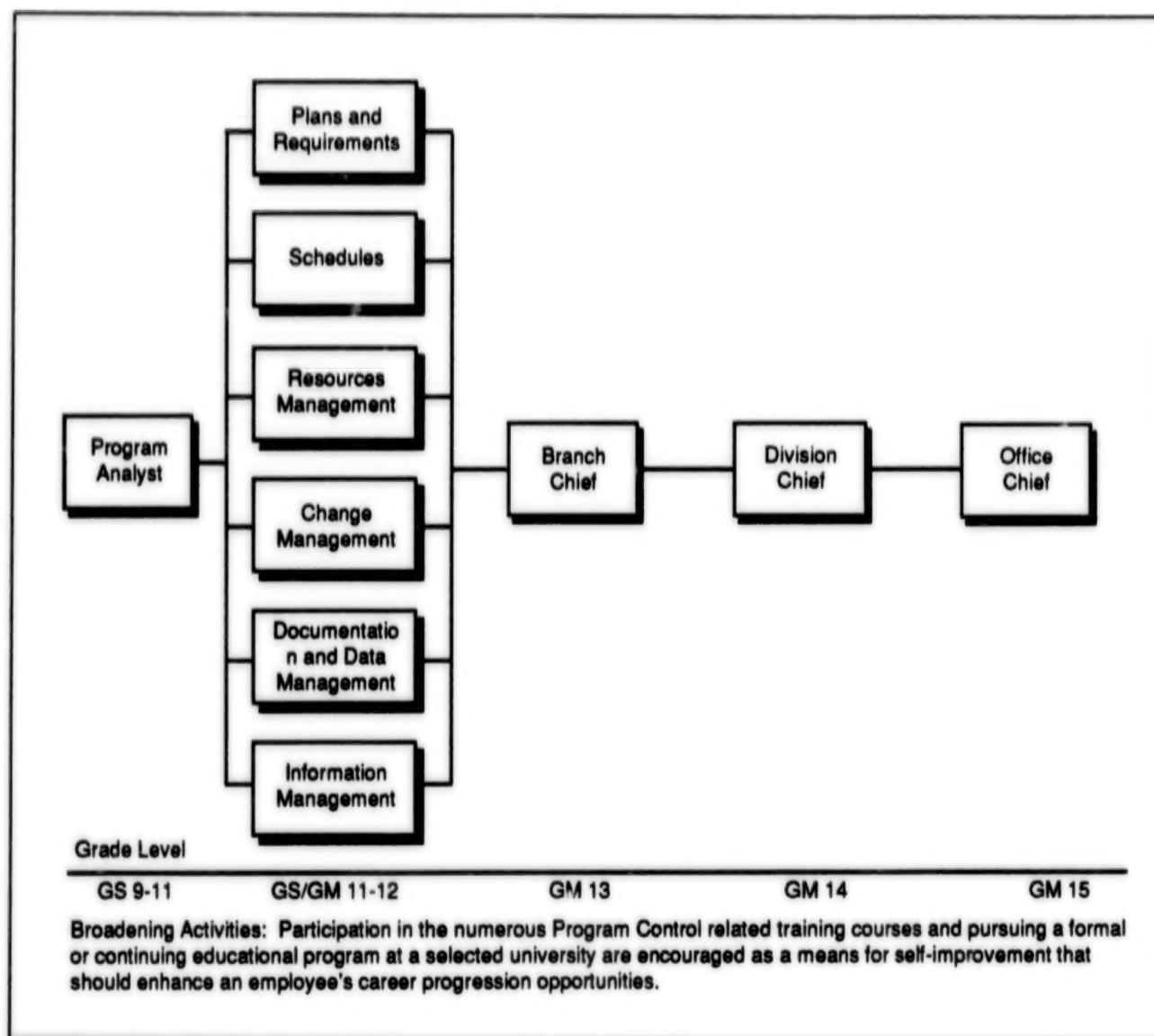


Figure 2. Example of Program Analyst Program Control Career Progression

- Formal or continuing educational programs selected by the individual for self-improvement.

Administrative Responsibilities

The responsibility for administration of the MSFC Program Control Program is:

- The Comptroller's Office will be responsible for the administration of the program; the technical and programmatic content of the program; preparation of Standard Individual Development Plans, including planning and scheduling rotational job

assignments, classroom instructional training and formal or continuing educational programs; and normal personnel supervisory responsibility for the two-year development period.

- Administrative Operations will be responsible for preparing and issuing Announcements for the MSFC Program Control Development Program and the individual selection process; providing classroom instructional training; and counseling individuals on formal educational opportunities.

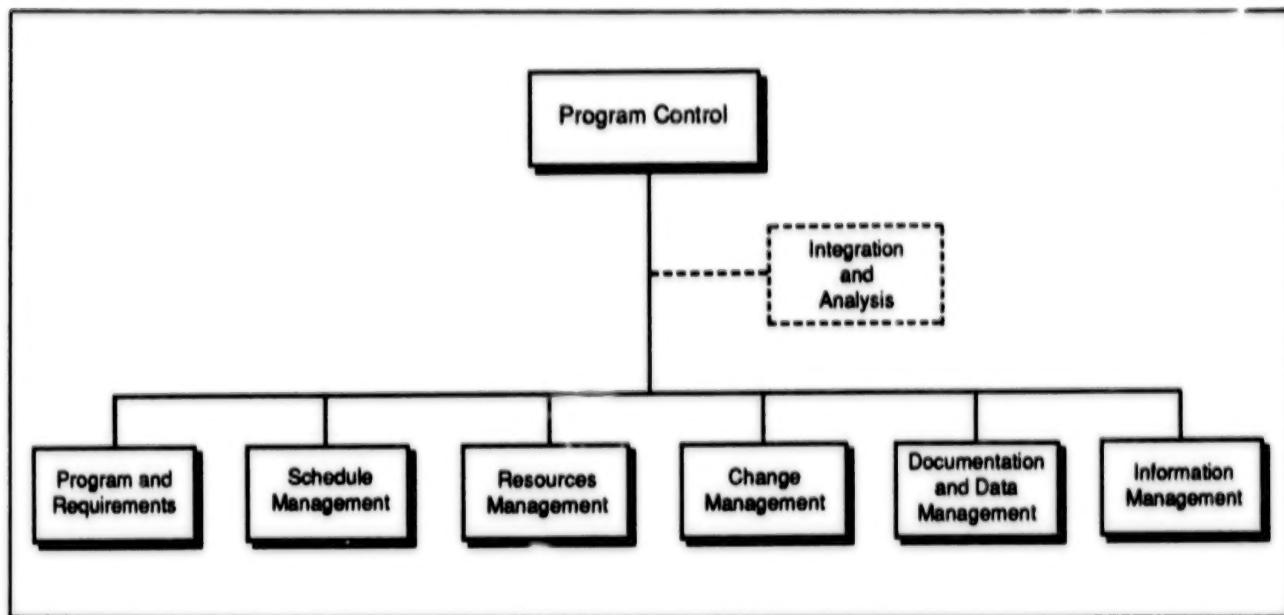


Figure 3. Program Control Functions

- Organizational elements providing on-the-job training will be responsible for providing the training set forth in the Standard Individual Development Plans for their particular area of responsibility and assisting with arrangements for classroom instructional training as appropriate. A mentor will be designated by the organizational element supervisor to assure that required on-the-job training is accomplished to the extent possible.

The participating individual, in concert with the mentor in the participating organization, will be responsible for completing (to the extent possible) on-the-job training requirements set forth in the Standard Individual Development Plans, planning and attending classroom instructional training, and other self-improvements such as formal or continuing educational programs.

Rotational Job Assignment. A major feature of the MSFC Program Control Development Program is that of rotational job assignments. Table 1 presents typical rotational job assignments to which participants will be assigned over the two-year training program.

Table 1. Examples of Rotational Job Assignments

Assignment	Months
Comptroller's Office	4
NASA Headquarters	2
Procurement Office	2
Project/Program Office	5
Engineering Cost Group	3
S&E Resources Management	3
Configuration Management	3
Resident Office	2
Total	24

These job assignments will allow the individual to receive on-the-job training to satisfy the training requirements set forth below.

Training Requirements. Table 2 lists typical training requirements for each job assignment. This on-the-job training, coupled with classroom instructional training conducted during the two-year period, will provide the individual with the training needed for each Program Control area. Additionally, it should prepare the individual for job opportunities of greater responsibility on his or her career development path.

Table 2. Typical Training Requirements for Each Job Assignment

NASA HEADQUARTERS	
Program Office	NASA Comptroller
- Organization Structure	- Organization Structure
- Roles and Responsibilities	- Roles and Responsibilities
- Working Relationships	- Working Relationship With Program Office
Field Center Program Offices	Independent Assessments
NASA Comptroller	- Non-Advocacy Review Assessments
Other NASA HQ Offices	- Interactions With OMB/Congress
	- Federal Budget Process
	- NASA Budget Process
COMPTROLLER'S OFFICE	
POP Process	Contractor Reporting of Correlated Cost and Performance Data (533 Reports)
Institutional Operating Plan	Performance Measurement System
Research and Program Management	NASA Financial Management System
Budget	NASA/MSFC Accounting System
Manpower Planning	Comptroller Office
- 918 Report	- Organization Structure
- Manpower Management Info System	- Roles & Responsibilities
Resources Management Info System	- Financial Management Operations
Federal Budget Process/NASA Budget Process	- Working Relationships
Receipt, Allocation and Control of Funds	Program and Project Office
- 504 and 506 Reports	NASA Comptroller
- Resources Authority Plan	NASA Program Offices
NASA Organization	Construction of Facilities Budget Process
MSFC Organization	Program Support Requirements
Program Control Overview	Project Planning Process
PROJECT/PROGRAM OFFICE	
Project Plans and Requirements	Budgeting
- Project Plan	- Project Budgets
- Management Plan	- Contractor Budgets
- Implementation Plans	- 533 Reports
- Requirements and Specifications	- Performance Measurement
Schedules	- Cost Analysis
- Logic Networks	Project/Program Office
- Project Schedules	- Organization Structure
Master	- Roles & Responsibilities
- Supporting	- Working Relationships
- Status/Reporting/Analysis	S&E
Work Breakdown Structure	Procurement
- Project WBS	Project/Program Office
- Contract WBS	
PROCUREMENT OFFICE	
Contract Management	Pricing
- Procurement Planning	- Contract Pricing
- Solicitation Process	- Rates & Factors
(Including SEB Process)	- Inflation Factors
- Contract Negotiation	- Overhead/G&A Rates
- Contract Administration	- DCAA/DCMC Role and
- DCMC Role and	Responsibilities
Responsibilities	- Forward Pricing
- Award Fee Process	
- Change Assessment	

Table 2. Typical Training Requirements for Each Job Assignment (cont.)

S&E RESOURCES MANAGEMENT OFFICE		ENGINEERING COST GROUP
Research and Technology Operating Plans	OAET Budget Process	Cost Estimating Techniques - Parametric - Analogy - Bottom-up
Institutional Planning Budgeting Process	S&E Directorate - Organization Structure - Roles and Responsibilities	Cost Estimating Relationships - Cost Modeling - Cost Risk Assessment - Economic Benefits Analysis - Redstar Data Base - Sensitivity Analysis - Trade Studies
Budget Execution - Source of Funding	Relationships to Program/Project Offices - Program Support Agreements - Program Support Requirements	
Manpower Planning/Control - Skills Analysis		
Purchase Requests		
Facilities and Equipment Requirements		
CONFIGURATION MANAGEMENT DIVISION		
Configuration Management Division - Organization Structure - Roles & Responsibilities - Working Relationships	Change Control Boards - Organization Structure - Membership - Operation	
Program/Project Offices	Tracking and Accounting System	
S&E Laboratories	Verification	
Safety and Mission Assurance	Documentation and Data Management System - Data Requirements - Data List - Data Procurement Document - Data Classification	
Configuration Management System - Identification - Control - Accounting - Verification	Documentation Tree	
Configuration Mgmt. Requirements	Specification Tree - Program - Project - Contract End Item - Critical Procurements	
Change Process - Engineering Change Request - Engineering Change Proposal - Change Control Board Directive - Change Flow - Change Integration	Interface Control - Requirements - Documents	
Baseline Reviews - Preliminary Requirements Review - Preliminary Design Review - Critical Design Review - Design Certification Review - Configuration Inspection - Acceptance Review	Document Processing - Electronic Processing - Archiving - Repository	
RESIDENT OFFICE		
Resident Office - Organization Structure - Roles & Responsibilities - Working Relationships	Contractor (cont.) - Internal Planning & Control System - Work Authorization System - Interdivisional Work Authorizations	Contractor (cont.) - General and Administrative Expenses
Program/Project Office Contractor	- Subcontract Management	- Preparation of Contractually Required Data
Defense Contract Management Command (DCMC)	- Internal Functional Organizational Relationships	- Direct Budgets
Defense Control Audit Agency (DCAA)	- Contractor Overhead/Burden	- Requirement Determination
Contractor - Organization Structure and Responsibilities	- Requirements	- Direct Budget Allocation
	- Approvals	- Cost Collection
	- Budget Allocations/Control	- Statusing
		- Cost Reporting
		- DCMC

Training Courses. Table 3 identifies numerous training courses available to MSFC employees. The training courses are extracted from the latest issue of the *MSFC Training Course Catalog* and have been grouped into the various Program Control functional areas to provide the individual with information on the many related course opportunities available. The list is representative and not all inclusive. The designation "N/A" means that the information was not available at time of printing. Some of the courses listed may no longer be available or may have changed. Some new training courses may become available that are not listed. For these reasons, it is important that the participant and his or her supervisor or mentor consult with the MSFC Training Branch in planning individual training needs.

Because of the large number of training courses available in certain functional areas, it will be necessary that the individual work with his or her supervisor and mentor in selecting the minimum essential courses needed to successfully complete the program. The Program Control Overview course is considered mandatory for this program. It will be presented locally on an ad hoc basis.

Continuous Self-Improvement Program
 Individuals selected for the Program Control Development Program are encouraged to participate in a formal or continuing educational program. There are many opportunities for individuals to seek self-improvement through various educational programs relating to the Program Control career path:

- Graduate programs at a selected university:
 - Master of management at the University of Alabama at Huntsville (UAH), which requires an undergraduate degree in engineering.

- Master of Science in engineering (with options in industrial engineering, systems engineering, etc.) and Master of Science in operations research at UAH.
- Master in engineering or a Master of business administration in Auburn University's "Outreach Program."
- Master of Science in industrial management at the University of Tennessee Space Institute.
- Master of business administration at Alabama A&M in cooperation with Pennsylvania State University. The MBA curriculum is specifically designed to give the student an opportunity to obtain a degree in business, regardless of the field in which he or she majored at the undergraduate level.
- Masters degrees in a number of non-engineering areas at the Florida Institute of Technology.
- Continuing education programs:
 - UAH Division of Continuing Education offers numerous educational opportunities designed to enhance professional and personal development. Continuing education credit courses enable students to pursue an undergraduate or graduate degree. Continuing education non-credit short courses and certificate programs provide quality training and education for professional and personal development. Especially noteworthy is the Project Management Certificate Program, a non-degree program requiring about 81 hours of classroom work over a period of about six months. A certificate from UAH or the Project Management Institute is awarded upon successful completion of the program.

The details of the above and other educational programs are available in the Personnel Development Division, Administrative Operations Office, MSFC. Individuals electing Program Control as a career development field are encouraged to give serious consideration to the many educational program opportunities available to them.

Upon completion of the MSFC Program Control Development Program, individuals will be assigned to a permanent position in a va-

cancy in the Program Control discipline commensurate with his or her position (title, grade and series) and career goals.

The MSFC Program Control Development Program offers no guarantees of promotion or career changes, except for those contained in the paragraph "Selection Process" above, but it does help individuals develop and grow personally and professionally, thus enhancing their value to the Center by improving their qualifications for future opportunities.

Table 3. MSFC Program Control Training Courses

Program Control Course Title	Course No.	Duration (hrs)	Resources Management Course Title	Course No. or Sponsor	Duration (hrs)
Program Control Overview	NASA	40	Federal Budget Process	40203	16
Project Management Workshop	41549	24	NASA Budget Process	N/A	N/A
Research and Development Contracting	40772	15	Cost/Manpower Mgmt. (includes Federal Budget Process and NASA Budget Cycle)	20125	16
Source Evaluation Procedures (for FED Procurements)	40776	24	Engineering Economics	30433	40
Source Evaluation Procedures	41554	15	Introduction to Financial Management	40249	40
Technical Project Management	40971	24	Budget Formulation	40177	40
Types of Government Contracts	40785	24	Budget Execution	40176	40
Basic Planning and Analysis	N/A	40	Cost Analysis and Estimating Techniques	40531	32
Introduction to Space Systems	N/A	36	Cost and Price Analysis	40192	40
Contract Changes and Terminations	40706	40	Advanced Cost and Price Analysis	41526	40
Federal Acquisition Process	41537	N/A	Budget Analysis Workshop	40174	40
Contractor Project Planning and Control System	N/A	N/A	Statistical Techniques for Analysis	30406	40
Project Organization Structure	N/A	N/A	Performance Management System	N/A	32
Applied Quality Assurance Operations	30964	15			
Cost Contracting	41532	40			
Contract Analysis and Control (for Project Management)	40704	09			
Problem Solving & Decision Making	20114	24			
Basic Procurement	40693	40			
Contract Management for Engineers	41522	40	Schedule Management Course Title	Course No. or Sponsor	Duration (hrs)
Contract Planning	41529	40	PERT-CPM Workshop	41547	20
Developing Work Statements for R&D Contracting	41535	32	Program Evaluation and Review Techniques	40945	24
Evaluating a Contractor's Performance	41536	40	Program Planning Network Risk Analysis	40949	20
Fundamentals of Contract Administration	40735	40	Computer Programs: Artemis	N/A	N/A
Fundamentals of Program Management	40935	40	Project II	N/A	N/A
Government Contract Negotiation Techniques	40740	40	Primavera		
Techniques of Negotiating	40780	24	Timeline		
Government Contract Negotiations Negotiations	40741	40	Quicknet		
Management Analysis and Review	41546	40			
	40509	40			

Table 3. MSFC Program Control Training Courses (cont.)

Change Management Course Title	Course No. or Sponsor	Duration (hrs)	Information Management Course Title	Course No. or Sponsor	Duration (hrs)
Configuration Management of Software	40930	24	Managing Information: Making Information Work for You	41558	02
Configuration Management	UAH	09	Workshop in Management Information Systems	90383	02
Integrated Configuration Management	UAH	40	Presenting Data in Graphs Charts and Tables	40515	24
Advanced Configuration Management	Tech Trng Corp.	24	Data Base Systems	90176	40
Strategies & Techniques for Configuration Management	Tecn Trng Corp.	16			
Basic Configuration Mgmt./ Advanced Config. Mgmt.	CDM Consultants	32			
Acquisition Techniques for Configuration	SCITEK	24			
Management Practitioners					
Basic Data Management	Tech Data Inc.	16			
Data Management Course, Number 15934	Navy Consld. Civ Pers Office	N/A			
Configuration Management II	Inst. of Config. Mgmt/Arizona		Plans and Requirements		
Course I-Documentation and Change MGMS		24	Course Title	Course No. or Sponsor	Duration (hrs)
Course II-Requirement Specifications Review		24	Systems Engineering Process	NASA	36
Course III-Configuration Definition & Documentation		24	- Systems Engineering Process		
Course IV-Engineering Change Control and Traceability		24	- Mission Need Statement		
Course V-Change Boards		24	- System Requirements/ Specifications		
Change Administration		24	- Implementation Plans		
Course VI-Organize and Manage Requirements			- Baseline Reviews		
Course X-CMII for Executives (Generic for Public)		08	SRM & QA Process	N/A	N/A
Course XI-CMII for Executives (for Onsite)		04	Fundamentals of Logistics Management	40490	40

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NASA'S ATTACK ON COSTS

by George M. Low

If we don't do something about the high cost of doing business in space, and do it soon, our nation's space program is in deep trouble. We are on the verge of exciting new discoveries in space science, but we cannot follow through as rapidly as we should because we can't afford it. We see before us many important space applications, but we cannot move out as rapidly as we should because we can't afford it. Most important of all, we may lose our hard-won worldwide leadership in space, if we don't find a way to do more for our money! To put it another way, we are doing less than we should do in space because things are so expensive, and because we are working under very tight budgetary constraints. There is very little we can do about the budget—it is imposed by external forces, and there are many other pressures on it; but there is a great deal we can do about costs. Doing something about the high cost of doing business in space is today's biggest challenge.

Basically, when we started out in this business 14 years ago, launch costs were overridingly important. We crammed everything we could into each launch, and optimized our satellites for low weight, low volume and high performance. Payload costs were clearly secondary considerations. This resulted in spacecraft tailor-made for each mission, with its own customized subsystems and components. Every piece was designed to the limit, with low margins and low tolerances. The net result was that most systems could be used only for the purpose for which they were originally intended, and after use in one satellite, were discarded in favor of new systems designed for the next mission. Furthermore, the low design tolerances required a tremendous number of tests and enormous volumes of paperwork to achieve absolute control. In other words, we were forced to perform very

expensive developments and then used the spacecraft only once or twice before starting on the next very expensive development. We have built many one-of-a-kind items, and have demanded the utmost in performance from them. Simple statistics bear this out. Today we have 52 operating civilian spacecraft. By the end of next year we will launch 35 more, for a total of 87. These 87 represent 43 different spacecraft types—on the average each spacecraft is flown only twice!

But things are different now. Payloads have become more complex, while launch costs have come down . . . This means that we should now optimize our payloads for low cost and high reliability, and not for minimum weight and maximum performance as we did in the past. I am convinced that if we do this, we can drastically reduce the cost of doing business in space. And this, I believe, is as great a technological challenge as everything else that we have done in space. . . In the design phase, the following principles are important:

- *Don't re-invent the wheel.* Use the best that is available from other programs. In all of the commercial firms I have visited, "not invented here" is unheard of. All tear down their competitor's product, study it, analyze it, cost it and make use of the best ideas in it, as long as they do not infringe on patent rights.
- *Standardize.* This applies to parts, components, modules, subsystems and entire systems. (There are only two chassis for the entire line of Sears television sets, and even they contain many common modules.)
- *Design for low cost.* Involve production engineers in the earliest stages of design

to help eliminate those things that will be difficult to produce.

- *Design to minimize testing and paperwork.* Simply stated, this means: take advantage of reduced weight and volume constraints and use standard parts, larger margins, and larger safety factors. (In Apollo we spent millions of dollars—on tests and paper—to be sure we did not exceed the “fracture mechanics” limits on our pressure vessels. A few extra pounds in tank weights would have completely eliminated that problem, and the testing and paperwork along with it.)
- *Recognize that different systems can accept differing degrees of risk . . .* A Shuttle life support system must be more reliable than a simple experiment in the Shuttle payload bay. The cost of a system should reflect the acceptance of risk in those instances where this is possible.
- *Know your costs.* None of the things I have said has any meaning if we don't know how much each element costs. The area of accurate cost estimating is one where we have a great deal to learn. Yet it is an area which *has been developed*.
- *Trade features for cost.* This follows naturally from the previous item. Once we know how much something costs, then we can ask ourselves whether it is really worth it. Many of our so-called “requirements” really aren't that firm, and should be stated as “goals,” to be re-examined in terms of cost.
- *Pay particular attention to the few very high-cost items.* In many designs some small percentage of the items amount to most of the costs. By knowing the costs, and by listing items in order of descending costs, it becomes possible to devote a

great deal of attention to the high-cost items—generally with profound results.

In the implementation phase, I would emphasize the following points:

- *Know your costs before you start.* This perhaps is the most fundamental of all requirements. Without exception, the NASA programs which have been in difficulty were the ones that had insufficient definition at the outset.
- *Set firm cost targets.* A desire for the “lowest possible cost” is not a good way to approach the job. A firm and absolute cost ceiling should be established for each job.
- *Meet the established cost targets.* Don't blame cost growths above target on “external forces.” Find ways to meet the targets, no matter what happens. This means that we have to become more productive in one area, if another area exhibits an “unavoidable” cost increase.

In summary, we must find ways to design for lower costs, we must know our costs, and we must set out to meet those costs . . .

In my years in the space program, and especially during the years when I had some first-hand experience as a project manager, I gained a tremendous respect for American industry . . . That industry rose to the challenge of Sputnik in 1957, and brought us to a position of world leadership in space. Today that same industry faces a new challenge—the challenge of doing more for less money.

It is up to you to apply the same skills, ingenuity and competitive spirit that allowed us to meet the challenge of 1957 to now meet the challenge of the 1970s—to preserve U.S. leadership in space through a productive program at a price the nation can afford.

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